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T.W. Moynihan
S.T. Lamson
A. Moucessian
J.O. Igwemezie, Ph.D.

prepared for
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RAIL PROFILE GRINDING

Phase III

prepared for

Transportation Development Centre
Policy and Coordination Group
Transport Canada

by

T.W. Moynihan
S.T. Lamson
A. Moucessian
J.O. Igwemezie, Ph.D.

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Canadian Institute of Guided Ground Transport
Queen's University at Kingston, Ontario
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16. Abstract

The third phase of the rail profile grinding research study examines both traditional corrective rail grinding practices and contemporary preventive rail grinding techniques. Actual grinding production on CP Rail tracks was monitored and analyzed to determine the precision and consistency of the normal grinding process in producing the targeted rail profiles. A total of 71 rails were examined, of which 33 were high rails, 34 were low rails, and 4 were in tangent track. The preventive grinding technique, which is based upon NRC preventive grinding recommendations, specifies frequent grindings to remove small amounts of steel from the rail head contact surfaces before significant surface fatigue defects can develop. This work involved field testing at three test locations on BC Rail tracks (a 6° curve, a section of tangent track, and a 3° curve) and two similar test sites on CP Rail tracks (a 6° curve and a 3° curve). Grinding was performed at intervals of approximately 5 MGT on the BC Rail test sites while the CP Rail test sites were ground at approximate intervals of 10 MGT. Each test site was periodically monitored for rail head loss, surface cracking, rail lubrication, sub-surface cracking and plastic flow. Additional tests were conducted to evaluate the dependence of metal removal rate on grinding speed. Finite element analysis was performed on 136 lb full and worn rail sections to examine the variation in rail stress. The results showed that rail internal stresses increase with the level of rail head wear.

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16. Résumé

La troisième phase de l'étude sur le reprofilage des rails s'est attachée tant aux méthodes traditionnelles d'entretien correctif qu'à celles plus modernes d'entretien préventif. Les opérations de meulage des rails chez CP Rail ont été examinées de près et analysées dans le but de vérifier la précision et l'uniformité du meulage aux profils décidés. Au total, 71 rails ont été examinés, 33 étant en file haute, 34 en file basse et 4 en alignement. Fondée sur les recommandations du Conseil national de recherches, la technique de meulage préventif consiste à effectuer des meulages fréquents dans le but d'enlever de petites quantités de métal des surfaces de contact du champignon de manière à prévenir l'apparition de signes évidents d'usure due à la fatigue dans cette partie du rail. La recherche a consisté à essayer une technique de meulage préventif sur trois tronçons de voie appartenant à BC Rail (une voie en courbe à 6 degrés, un alignement et une voie en courbe à 3 degrés) et deux tronçons comparables de CP Rail (deux courbes à 6 et 3 degrés, respectivement). Les meulages ont été effectués au bout de 5 MGT et de 10 MGT de trafic environ pour les voies de BC Rail et de CP Rail, respectivement. Les contrôles effectués périodiquement en ces endroits ont porté sur l'usure du champignon, la fissuration superficielle et en profondeur, l'effet de la lubrification des rails et l'écoulement plastique. D'autres essais effectués ont approfondi le rapport entre vitesse d'avancement et quantité de métal enlevé. Une analyse d'élément fini fut accomplie sur des tronçons de rail nouveau et usagé, ayant une pésanteur de 136 lb., dans le but d'examiner la variation de tension sur le rail. Les résultats ont montrés que la tension interne sur le rail augmente avec le niveau d'usure du champignon.

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EXECUTIVE SUMMARY

The third phase of the rail profile grinding research study was concerned primarily with establishing and evaluating rail maintenance expertise and procedures. Specifically, the objectives were:

(a) To monitor the consistency of production and long term performance of the designed rail profile.

(b) To develop a simple gauge for field verification of grinding performance, a grinding manual and some new continuous welded rail (CWR) wear limit criteria.

(c) To examine the feasibility and economics of introducing a preventive maintenance grinding philosophy involving grinding curved sections more frequently using fewer and finer grinding stones and operating at higher speeds.

The first two objectives were directed specifically at CP Rail track maintenance operations. Throughout 1986 and 1987, grinding production on CP trackage was monitored and analyzed to determine the precision and consistency of the grinding process in producing the targeted rail profiles. This work facilitated the development and field testing of a simple rail profile measurement gauge and provided the necessary data and experience from which a grinding manual was prepared. The evaluation criteria were based upon the following considerations:

- adequacy of metal removal (i.e. rail grinding rate);
- achievement of CP-specified rail profiles;
- consistency of performance.

Regarding the assessment of rail grinding performance on CP Rail, the following conclusions are offered:

(a) Proportion of depth of metal removed which was within specifications was as follows:

Centre zone:	Grinder A 40 percent, Grinder B 39 percent
Gauge zone:	Grinder A 33 percent, Grinder B 36 percent
Field zone:	Grinder A 47 percent, Grinder B 73 percent

(b) The clearest observation with regard to points which fell outside the specified ranges concerned the centre zone grinding. For this zone Grinder B's metal removal was too high while Grinder A's was too little.

(c) A higher proportion of contact band radii of curvature of rails ground by Grinder B was within specification (37 percent for Grinder A versus 54 percent for Grinder B).

The third objective was conducted as a collaborative effort between BC Rail, CP Rail, the National Research Council (NRC) of Canada and the Canadian Institute of Guided Ground Transport (CIGGT). This work involved the field testing of a preventive rail grinding technique at three test locations on BC Rail trackage and two similar test sites on CP Rail tracks. The technique, which is based upon NRC preventive grinding recommendations, specifies frequent grindings to remove small amounts of steel from the rail head contact surfaces before significant surface fatigue defects can develop. Each test site was periodically monitored for rail head loss, surface cracking, rail lubrication, sub-surface cracking and plastic flow. Additional tests were conducted to evaluate the dependence of metal removal rate on grinding speed.

Observations made throughout the preventive maintenance grinding experiments, conducted on CP Rail and BC Rail tracks, support the following:

(a) Preventive grinding programs can effectively maintain rail head surfaces free of major fatigue defects. An optimum interval for a grinding cycle is likely to lie somewhere between 10 and 18 MGT for curves of up to 6°. In the limited test comparison with the 5 MGT preventive grinding cycle and the 25 MGT corrective cycle, the preventive grinding cycle conducted at 10 MGT intervals appears to be more economical in terms of both grinding effort and metal removal.

(b) To ensure effective control of fatigue cracks at sharp curves, the amount of metal removal on the gauge corner should be at least twice that of the centre region of the rail head. Smooth transitions from facet to facet on the gauge corner are critical if stress concentrations, and therefore accelerated wear, are to be avoided.

(c) The amount of rail head metal lost due to preventive grinding throughout the duration of testing did not appear to significantly reduce the useful life of the ground rails.

(d) It is strongly indicated that preventive grinding practice will significantly increase rail life. Rail head wear, rather than surface fatigue defects, may ultimately become the criteria controlling the replacement of rails. However, further detailed examination of the effect of rail head metal loss on rail fatigue should be performed to establish appropriate wear limits.

(e) The speed grinding test results indicate that the amount of metal removed is essentially constant at speeds ranging between 6 and 10 mph and is sufficient in magnitude for preventive grinding.

Based upon the results of this study the following recommendations are provided:

(a) Stricter quality control procedures, including field verification of ground rail contours, should be used to ensure optimal rail conditions.

(b) The relationship between head loss and increased rail fatigue on curved track should be examined in detail.

SOMMAIRE

La troisième phase de l'étude sur le reprofilage des rails a eu pour but principal de cerner les connaissances et les pratiques relatives à la maintenance des rails et d'en faire l'appréciation. Quant aux objectifs particuliers, ils ont été les suivants :

a) Vérifier l'uniformité du meulage et la tenue dans le temps des profils réalisés.

b) Réaliser un profilomètre facile d'emploi pour les contrôles in situ, élaborer un manuel de meulage et définir certains nouveaux critères d'usure admissible applicables aux longs rails soudés.

c) Faire une étude de faisabilité technico-économique d'un programme pour l'entretien préventif des rails, faisant appel à un meulage plus fréquent des rails formant les courbes et utilisant pour cela des meules plus fines et moins nombreuses mais tournant plus rapidement.

Les deux premiers objectifs ont visé principalement le programme d'entretien des voies de CP Rail. Tout au long de 1986, cette société a contrôlé de près les résultats des opérations de meulage des rails et les a analysés dans le but de vérifier la précision et l'uniformité du meulage aux profils décidés. Ces travaux ont facilité la mise au point et l'essai in situ d'un profilomètre facile d'emploi, et ils ont fourni la matière pour un manuel de meulage faisant la synthèse de toutes les données et de toute l'expérience accumulées. Quant aux critères d'évaluation utilisés, ils ont été les suivants :

- quantité du métal enlevé;
- réussite dans la réalisation des profils décidés;
- uniformité des résultats.

Les résultats des opérations de meulage entreprises par CP Rail autorisent les conclusions suivantes :

a) La proportion des rails où la quantité de métal enlevé est restée à l'intérieur des limites spécifiées a été comme suit :

Zone centrale : Meuleur A, 40 p.100, meuleur B, 39 p.100.
Coin intérieur: Meuleur A, 33 p.100, meuleur B, 36 p.100.
Coin extérieur: Meuleur A, 47 p.100, meuleur B, 73 p.100.

b) Les résultats les plus éloignés des limites spécifiées concernent la zone centrale. A cet égard, le meuleur B a enlevé trop de métal et le meuleur A pas assez.

c) Pour ce qui est du respect des limites spécifiées pour les rayons de courbure de la table de roulement, le meuleur B a donné de meilleurs résultats que le meuleur A: 54 p.100 par rapport à 37 p.100 pour ce dernier.

Le troisième objectif visé a fait l'objet d'une action coopérative entre BC Rail, CP Rail, le Conseil national de recherches du Canada (CNR) et le Canadian Institute of Guided Ground Transport (CIGGT). La recherche a consisté à essayer une technique de meulage préventif à l'égard de trois tronçons de voie appartenant à BC Rail et de deux tronçons comparables appartenant à CP Rail. Fondée sur les recommandations du CNR, cette technique de meulage préventif consiste à effectuer des meulages fréquents, dans le but d'enlever de petites quantités de métal des surfaces de contact du champignon, de manière à prévenir l'apparition de signes évidents d'usure due à la fatigue dans cette partie du rail. Les contrôles effectués périodiquement en ces endroits ont porté sur l'usure du champignon, la fissuration superficielle et en profondeur, l'effet de la lubrification des rails et l'écoulement plastique. D'autres essais effectués ont approfondi le rapport entre vitesse d'avancement et quantité de métal enlevé.

Ces opérations de meulage préventif ont fait l'objet d'observations soutenues desquelles on a pu tirer les conclusions suivantes :

a) Le meulage préventif est efficace pour maintenir les surfaces de contact rail-roue exemptes de signes évidents de fatigue. L'intervalle optimal entre deux passages se situe probablement entre 10 et 18 MGT pour les courbes à 6 degrés. Des comparaisons peu étendues avec les résultats des programmes de meulage préventif et correctif, menés respectivement à intervalles de 5 et de 25 MGT de trafic, montrent que le meulage préventif au bout de 10 MGT est le plus économique, tant en puissance consommée qu'en quantité de métal enlevé.

b) La prévention efficace des fissures de fatigue, là où les courbes sont prononcées, suppose que la quantité de métal enlevé au coin intérieur soit au moins le double de la zone centrale. Il faut aussi que la transition d'une facette à l'autre du coin intérieur soit impérativement en douceur pour éviter la concentration de contraintes et, donc, l'accélération de l'usure.

c) Il ne semble pas que la quantité de métal enlevé du champignon par le meulage préventif ait pu réduire sensiblement la durée de vie utile des rails meulés.

d) Tout semble montrer que le meulage préventif pourra accroître sensiblement la durée de vie des rails. On pense que l'usure du champignon remplacera la fatigue de la surface de contact comme critère de mise au rebut d'un rail. Néanmoins, le rapport entre perte de métal du champignon et fatigue devra être approfondi dans le but d'établir une fourchette appropriée d'usure admissible.

e) Les essais sur la vitesse du meulage ont montré que la quantité de métal enlevé ne varie guère aux vitesses d'avancement situées entre 10 et 16 km/h et que cette quantité donne les résultats voulus.

Les résultats obtenus autorisent les recommandations suivantes :

a) Rendre plus rigoureuses les techniques de contrôle de la qualité, y compris les vérifications profilométriques in situ, dans le but d'obtenir des résultats optimums.

b) Approfondir le rapport pouvant exister entre perte de métal du champignon et accroissement de la fatigue dans le rail.

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1.0 INTRODUCTION

Heavy-haul railway operators are commonly faced with extensive track maintenance requirements, especially on curves. The high costs associated with maintaining trackage somewhat mitigates the economic advantage inherent in heavy-haul operation. Therefore, measures taken to reduce the level of track damage produced during normal heavy-haul operation will provide significant cost benefit to the operator.

Standard three piece freight trucks require some contact between the wheel and high rail gauge face to properly negotiate curves. Wear at the rail head gauge corner resulting from this contact is unavoidable, but can be controlled by reducing such contact. Any change in the contact locations of wheels on the rail head running surfaces which produces a large rolling radius differential between the high and low rail will lead to reduced wear of the high rail's gauge face and retard plastic flow and corrugation of the low rail head running surface.

Another major source of rail damage which has been identified by researchers is the "false flange" of a worn wheel tread profile. Contact between the "false flange" and the low rail head during curving promotes the development of corrugations on the rail's running surface. Once corrugation has been initiated, the high dynamic loading induced by the heavily loaded wheels of heavy-haul vehicles rolling over the corrugated surface rapidly accelerates and propagates the rail damage.

Grinding practices on Canadian railways have been traditionally concerned with the removal of corrugations and damaged material from the rail and restoring its surface geometry to a faceted reproduction of the original crown profile. This grinding is usually done after a significant amount of rail deterioration has occurred.

In 1982, a rail profile grinding test program was conducted on CP Rail trackage between Golden and Roberts Bank in British Columbia [1]. This track through the Rocky Mountains, over which heavy-haul coal unit trains operate, was experiencing exceptionally severe rail maintenance problems. The work was primarily concerned with the adaptation of an asymmetrical rail profile grinding technique, originally developed to reduce rail wear on Australian heavy-haul railways, to increase rail life on CP Rail's curved track. The specific objectives were three fold:

(a) Reduce corrugation (occurring mainly on low rails).

(b) Reduce gauge-corner shelling (occurring mainly on high rails).

(c) Reduce gauge-side wear (occurring mainly on high rails).

Three test curves (2°, 4° and 8°) were selected and monitored for a period of six months. From these observations it was concluded that:

(a) Grinding of the field side of low rail surfaces is effective in reducing corrugation.

(b) Grinding of the gauge corner of high rails is effective in reducing shelling.

(c) Too much gauge corner grinding can cause an increase in lateral wheel forces.

Consequently, a design for an asymmetrically ground rail profile was established and recommended for use on a large-scale trial basis.

In 1984, a second field grinding test program was conducted on the Cascade Subdivision of CP Rail's western main line [2]. The primary objectives of this second phase of work were to verify the performance of the CIGGT-proposed ground rail profile and to explore the possibility of further profile refinement. Specifically, the performance measures of interest were:

(a) The effect of rail grinding on the rate of regrowth of corrugation on low rails.

(b) The effect of rail grinding on the rate of gauge face wear and surface fatigue shelling on high rails.

A total of fifteen test curves (six of 4° and nine of 8°) were ground using experimental rail profiles developed by CIGGT, CN and CP Research. The test profiles were then monitored throughout a six month period following rail grinding during which time approximately 18 MGT of traffic passed over the rails. From these tests it was concluded that:

(a) The test grinding patterns for low rails produced significantly lower levels of corrugation than those at pre-grinding.

(b) The test grinding patterns produced improved rail surface conditions than those at pre-grinding.

(c) The test grinding patterns for high rails prevented further rail surface shelling and spalling.

(d) Gauge corner grinding may be varied over a substantial range without significantly effecting rail wear.

(e) One grinding pass every four months (12 MGT) is recommended over two passes every six months (18 MGT).

The effectiveness of asymmetrical rail profiles in controlling rail wear is evident from the results of the phase I and II work. Consequently, it was recommended that asymmetrical grinding patterns be used on all curved track and that alternatives to the present rail grinding schedules and practices be further examined.

In 1986, the third phase of this rail profile grinding research program began.

2.0 DESCRIPTION OF WORK

The third phase of the rail profile grinding research study was concerned primarily with establishing and evaluating rail maintenance expertise and procedures. Specifically, the objectives were:

(a) To monitor the consistency of production and long term performance of the designed rail profile.

(b) To develop a simple gauge for field verification of grinding performance, a grinding manual and some new continuous welded rail (CWR) wear limit criteria.

(c) To examine the feasibility and economics of introducing a preventive maintenance grinding philosophy involving grinding curved sections more frequently using fewer and finer grinding stones and operating at higher speeds.

The first two objectives were directed specifically at CP Rail track maintenance operations. Throughout 1986, grinding production on CP trackage was monitored and analyzed to determine the precision and consistency of the grinding process in producing the targeted rail profiles. This work facilitated the development and field testing of a simple rail profile measurement gauge and provided the necessary data and experience from which the CP Rail Grinding Field Manual was produced [3].

The third objective was conducted as a collaborative effort between BC Rail, CP Rail, the National Research Council (NRC) of Canada and the Canadian Institute of Guided Ground Transport (CIGGT). This work involved the field testing of a preventive rail grinding technique at three test locations on BC Rail trackage and two similar test sites on CP Rail tracks. The technique, which is based upon NRC preventive grinding recommendations, specifies frequent grindings to remove small amounts of steel from the rail head contact surfaces before significant surface fatigue defects can develop. Each test site was periodically monitored for rail head loss, surface cracking, rail lubrication, sub-surface cracking and plastic flow. Additional tests were conducted to evaluate the dependence of metal removal rate on grinding speed.

2.1 Rail Grinding Performance Measurement

The primary objective of these evaluations was to quantify the rail grinding performance of CP Rail's grinding contractors. The evaluation criteria were based upon the following considerations:

- adequacy of metal removal (i.e., rail grinding rate);
- achievement of CP-specified rail profiles;
- consistency of performance.

The data used for this evaluation was collected between May 1985 and October 1986 at 11 different sites on CP Rail track. Grinding was monitored on a total of 71 rails, of which 33 were high rails, 34 were low rails, and 4 were in tangent track. Of the 71 rails monitored, 30 were ground by one contractor *(identified as "Grinder A") and the remaining 41 were ground by* another contractor (identified as "Grinder B"). Table 2.1 summarizes the rails tested and grinding contractor at each of the 11 test sites.

Table 2.1: Summary of Rails Monitored for the CP Rail Grinding Performance Evaluation

Site No.	Subdivision	Contractor	Rails Ground
1	CP Heron Bay Subdivision	Grinder A	2 high rails 4 low rails
2	CP Galt Subdivision	Grinder A	2 high rails 2 low rails
3	CP Crowsnest Subdivision	Grinder B	10 high rails 11 low rails 1 left rail 1 right rail
4	CP Cascade Subdivision	Grinder B	5 high rails 5 low rails
5	CP Heron Bay Subdivision	Grinder A	3 high rails 2 low rails
6	CP Kaministiquia Subdivision	Grinder B	1 high rail 1 low rail
7	CP Ignace Subdivision	Grinder B	3 high rails 3 low rails
8	CP Brooks Subdivision	Grinder A	4 high rails 3 low rails 1 north rail 1 south rail
9	CP Brooks Subdivision	Grinder A	1 high rail 1 low rail
10	CP Cranbrook Subdivision	Grinder A	1 high rail 1 low rail
11	CP Cranbrook Subdivision	Grinder A	1 high rail 1 low rail

Rail profile measurements were taken before and after grinding at each test location using the CIGGT rail wear gauge. Data points were obtained at approximately 1/8" intervals across the rail head surface thus providing about 20 readings per profile. The number of possible readings was somewhat less in some instances where rails were transposed or severely worn. All measurements taken with the wear gauge are accurate to 0.001 inches and were repeated at least once to verify their accuracy. Additional measurements were made with a tape measure to determine the size and location of the contact band immediately following the grinding operation.

To facilitate subsequent data reduction and analysis, the rail head surface was divided into the three zones listed below:

(a)	field zone	(readings 1-7)
(b)	centre zone	(readings 7-14)
(c)	gauge zone	(readings 14-23)

Average grinding depths were then calculated over each of these three rail head zones. Grinding performance was then quantified by comparing the average depth of cut in each rail head zone with the acceptable ranges specified in the CP Rail Grinding Field Manual.

The post-grinding rail profiles were also examined to determine how closely they corresponded to the targeted grinding patterns. Additionally, the radius of curvature of each rail head surface contact band was calculated and compared with the acceptable ranges specified in the CP Rail Grinding Field Manual.

2.2 Preventive Maintenance Grinding

The preventive maintenance grinding technique under study specifies a series of more frequent rail grindings than in current practice, where less material is removed from the rail head at each grinding. Recommendations provided by the National Research Council identified three distinct levels of traffic volume which should not be exceeded between preventive grinding applications. They are:

(a) every 15 MGT for tangent rail;

(b) every 10 MGT for shallow curved rail;

(c) and every 5 MGT for sharply curved rail.

These recommendations recognize that rail degradation is generally most severe on sharp curves where heavy flange contact is most likely to occur while it is generally least severe on tangent track where flange contact is minimal. In performing such frequent grindings, any damaged material is removed before significant fatigue cracking can occur. This prevents crack propagation and ensures that the rail surface is maintained free of significant fatigue defects. The effectiveness of this approach was evaluated through observation of rail degradation on track sections subject to frequent rail grindings.

2.2.1 CP Rail Preventive Grinding Test

The preventive rail grinding experiments on CP Rail trackage near Golden, B.C., involved the frequent grinding and monitoring of two primary test sites. They were a 6° curve at mile post 55.8 and a 3° curve at mile post 55.5. The rails had been in service for three to four years and were exhibiting some fatigue cracking and moderate shelling. Each test location was assigned a site number which will be used throughout this report when referencing the data collected and observations made at that location. The site number allocations along with a description of the rails at each test location are provided below:

Test Site #1 - Mile post 55.8
6° left-hand curve
head-hardened Japanese superrail, 136 RE, 1984

Test Site #2 - Mile Post 55.5
3° right-hand curve
control-cooled Algoma rails, 136 RE, 1983

In addition to these primary test sites, it was necessary to establish two secondary grinding sites for use in testing modifications made to the NRC preventive grinding pattern prior to implementation at the primary test sites. These additional trial test sites were:

Test Site #3 - Mile post 54.8

Test Site #4 - Mile post 57.3

Before grinding the rails at the primary test locations, rail wear replicas were taken by NRC, rail plugs were removed by CP rail, rail profile measurements were carried out by CIGGT, and finally dye penetrant was applied to each location where the rail profile was measured and photographs taken of the rail head surface by CIGGT. The rails were then ground. Following the grinding, rail wear replicas along with rail profile measurements and rail surface photographs were taken at each test location.

Indications of fatigue crack development and propagation since the last preventive grinding cycle as well as the extent to which the grinding pattern used was able to eliminate surface defects such as cracks, plastic flow and corrugation were inferred from the photographs taken before and after grinding. The rail plugs were examined by NRC to determine the subsurface conditions of the rails. Comparison of the rail profile measurements obtained immediately before and after grinding facilitated calculation of average grinding depths and volumes of metal removed as well as quantitative measures of how closely the produced rail profile produced corresponded to the desired rail surface geometry.

The test period spanned roughly an eleven month period from September 19, 1986 through to August 13, 1987. During this period, the test sections were ground approximately every two months which corresponded to approximately 9 to 10 MGT of traffic between each preventive grinding cycle. Three site visits were made during the test period as summarized below:

Test 1 - 86/09/19
Test 2 - 87/06/09 to 87/06/13
Test 3 - 87/08/13

2.2.2 BC Rail Preventive Grinding Test

The preventive rail grinding field testing program involved the frequent grinding and monitoring of three test sites on BC Rail's Chetwynd Subdivision near Prince George, B.C. These included a six degree curve at mile post 410.4, a section of tangent track at mile post 470.8, and a three degree curve at mile post 471.1. The rails at all test sites were essentially new (of 1985 vintage) and in relatively good condition. Each test location was assigned a site number which will be used throughout this report when referencing the data collected and observations made at that location. The site number allocations along with a description of the rails at each test location are provided below:

Test Site #1 - Mile post 470.4
6° right-hand curve
high rail, 136 lb/yd RE, NKK VT, 1985/9
low rail, 136 lb/yd RE, NKK VT, 1985/9

Test Site #2 - Mile post 470.8
tangent track
west rail, 68 kg/m RE, BHP SC, 1985
east rail, 68 kg/m RE, BHP SC, 1985

Test Site #3 - Mile post 471.1
3° left-hand curve
high rail, 136 lb/yd RE, NKK VT, 1985/9
low rail, 136 lb/yd RE, NKK VT, 1985/9

Before grinding each location, rail wear replicas were taken by NRC, rail plugs were removed by BC Rail, rail profile measurements were carried out by CIGGT, and finally dye penetrant was applied to each location where the rail profile was measured and photographs taken of the rail head surface by CIGGT. The rails were then ground at normal speed (between 2 and 3 mph) using grinding patterns defined by NRC to relieve the gauge corner and produce a specified crown radius (initially between 12 and 14 inches) while removing only a small quantity of metal (initially 0.003" depth of cut). Following the grinding, rail wear replicas along with rail profile measurements and rail surface photographs were taken at each test location.

Indications of fatigue crack development and propagation since the last preventive grinding cycle as well as the extent to which the preventive grinding pattern was able to eliminate surface defects such as cracks, plastic flow and corrugation were deduced from the photographic records taken. The rail plugs were used by NRC to examine subsurface conditions within the rails. Comparison of the rail profile measurements obtained immediately before and after grinding facilitated calculation of average grinding depths and volumes of metal removed as well as quantitative measures of the grinding patterns ability to produce the desired rail surface geometry.

While the cost savings potential of extending the service life of rail in curved track through the implementation of preventive grinding practices are potentially large it must be noted that an operator's rail grinding costs will increase with the frequency of grinding. However, recognizing that the quantities of material removed during a preventive grinding cycle are intended to be significantly smaller than those removed in traditional rail grinding practice would seem to indicate that preventive grinding can be performed at substantially greater speeds than traditional rail grinding. This would of course allow an operator's grinding equipment to cover its territory more quickly thus allowing more frequent grinding passes. Therefore, an additional four test sites on a long section of tangent track between mile posts 472.0 and 475.0 were selected to perform speed grinding tests. The site number allocations and rail descriptions for these test locations are as follows:

Test Site #4 - Mile post 472.0
tangent
west rail, 68 kg/m RE, BHP BC, 1985/10
east rail, no measurements

Test Site #4a - Mile post 473.0
tangent
west rail, 68 kg/m RE, BHP BC, 1985/10
east rail, 68 kg/m RE, BHP BC, 1985/10

Test Site #5 - Mile post 474.0
tangent
west rail, 68 kg/m RE, BHP BC, 1985/10
east rail, 68 kg/m RE, BHP BC, 1985/10

Test Site #6 - Mile post 475.0
tangent
west rail, 68 kg/m RE, BHP BC, 1985/9
east rail, 68 kg/m RE, BHP BC, 1985/10

Rail replicas and rail profile measurements were taken prior to each speed grinding test. Single grinding passes were then made at speeds ranging between 4 and 10 mph. Again, rail wear replicas and rail profile measurements were taken immediately following grinding. Subsequent analysis of the rail profiles provided measures of the rate of metal removal and the grinder's ability to achieve the desired rail surface geometry at these elevated grinding speeds.

Testing on the BC Rail Chetwynd Subdivision occurred during the roughly 14 month period from September 17, 1986 through to November 2, 1987. Throughout the duration of this test period the preventive grinding cycle was performed at intervals of 4 to 6 MGT of traffic between grindings. A total of three site visits were made as itemized below:

Test 1 - 86/09/16 to 86/09/18
Test 2 - 87/04/12 to 87/04/15
Test 3 - 87/11/01 to 87/11/02

3.0 RESULTS

The measurements and photographs taken during all site visits, along with the results of subsequent data reduction and analysis, are provided in Appendices A through F of this report.

Appendices A, B and C provide details of the grinding quality evaluation, grinding rates and measured rail head profiles, respectively, for each test site monitored in the CP Rail grinding performance evaluation portion of this research programme. Appendices D, E and F provide details of the rail head surface conditions, measured rail head profiles and calculated grinding rates, respectively, for all test sites used during the preventive maintenance grinding tests.

3.1 Rail Grinding Performance Measurement

The rail profile data collected before and after grinding were evaluated against specifications provided in the CP Rail Grinding Field Manual. Table 3.1, which is reproduced from this grinding manual, gives the range of acceptable grinding depths. In addition, the manual specifies acceptable ranges for the radius of curvature of the rail contact band as 8 to 12 inches on high rails and 10 to 14 inches on low and tangent rails.

Table 3.1: Acceptable Range of Depth of Cut for a Standard Case
(full size grinder, one pass at 2.5 mph)

		Gauge Side	Centre	Field Side
High Rail	- min.	.020"	.006"	.010"
	- max.	.040"	.012"	.020"
Low Rail	- min.	.008"	.006"	.012"
	- max.	.016"	.012"	.040"
Tangent	- min.	.015"	.006"	.006"
	- max.	.030"	.010"	.012"

Source: *CP Rail Grinding Field Manual*

Tables A.1 through A.11, in Appendix A, list descriptions of the sites where grinding was monitored, together with average grinding depths measured at the field, centre and gauge zones of the rail head. The depth values were normalized to one grinding pass at a speed of 2.5 mph for ease of comparison with the CP grinding depth specifications. The tables also indicate the radius of curvature of the expected contact band of the ground rails calculated from the rail profile measurements. Two columns in each table are used for commenting on the quality of the grinding in producing the required depths and radii of curvature. Short comments are used (OK, high or low) to describe the results as within, higher or lower than the specified values, respectively.

The following factors were influential in the outcome of this evaluation. It is therefore important that the reader keep these points in mind when considering the comments on grinder performance:

- Selection of a position for the field, centre and gauge zones can influence their average grinding depths and volume of metal removed (it does not, however, affect the overall average grinding depth).

- Linear normalization of average grinding depths to one pass grinding at 2.5 mph is only valid for grinding speeds of 2 to 3 mph. Normalized grinding results outside this range are subject to non-linear error.

- To calculate the radius of curvature of the expected contact band, a circular arc is fitted to 4 measured points on the rail head. The value of the radius of curvature of such a circular arc can be affected by:

  (a) the selected data points, i.e. the zone over which the expected contact band was assumed to be;

  (b) the band width, which in these calculations was variable between 0.75 and 1.25 inches;

  (c) all the radius values calculated from data which is taken immediately after grinding. At this stage the shape of the rail head consists of several facets rather than a smooth curve. This can result in artificially low radii of curvature.

Table 3.2 summarizes the results of the grinding depth evaluation. Comparable percentages of grinding depths found to be within the specifications for the centre (A's 40 percent versus B's 3 percent), gauge (A's 33 percent versus B's 36 percent) and field zones (47 percent for A compared to B's 73 percent) are provided for both grinding contractors. Additionally, the results also indicate percentages of rails at which the depth of cut was above and below specification.

Table 3.2: Summary of Grinding Depth Evaluation

Grinding Contractor	Total No. of Ground Rails	Field Zone %			Centre Zone %			Gauge Zone %		
		High	OK	Low	High	OK	Low	High	OK	Low
A		30	23	47	30	17	40	43	7	360
B		41	10	73	17	61	39	0	29	364

The following points were noted in relation to the values which fell outside the specified ranges:

- over the centre zone, grinder B removed too much metal while grinder A removed too little;

- over the gauge zone, grinder A did not remove enough metal while grinder B's metal removal was almost equally distributed between too much and too little;

- over the field zone, both Grinder A's and Grinder B's metal removal was similarly distributed between too much and too little.

The evaluation of the radii of curvature of the rail head surface contact band, as summarized in Table 3.3 below, indicates that a higher proportion of rails ground by Grinder B were within the specifications than were those ground by Grinder A. The numbers enclosed in parentheses represent revised percentages for in specification radii of curvature based upon using an acceptable range of between 8 and 14 inches for both the high and low rail.

Table 3.3: Summary of Radius of Curvature Evaluation

Grinding Contractor	Total No. of Ground Rails	Radius of Curvature %		
		High	OK	Low
A	30	0	27(37)	73 (63)
B	41	10 (7)	37 (54)	53 (39)

As previously indicated, the CP Rail Grinding Field Manual specifies values between 8 and 12 inches for contact band radii of curvature on high rails while for low and tangent rails a contact band radii of curvature between 10 and 14 inches is deemed acceptable. Relaxation of the specification significantly increases the percentage of rails found to have contact band radii of curvature within the acceptable range.

A closer examination of the results in Tables A.1 through A.11 which fall outside the specified ranges would indicate that in general Grinder B's values were above or below the specifications by a smaller margin than were Grinder A's.

3.2 Preventive Maintenance Grinding

The remainder of this section details the observations and analyses resulting from the work conducted by CIGGT during the preventive maintenance grinding experiments on CP Rail and BC Rail. Additional results of work conducted by the NRC have been independently documented in NRC Report No. TR-TM-012 [4].

3.2.1 CP Rail Preventive Grinding Test

The first set of tests on CP Rail tracks near Golden, B.C., were conducted on September 19, 1986. Prior to grinding, a dye penetrant was applied to the rail head and photographs taken of the rail head surface condition. Figure D.1 illustrates the generally good overall condition of the high and low rails of the 6° curve (test site #1) before grinding. Both rails at this site were free from significant surface fatigue defects, with the exception of very slight cracking on the gauge corner of the high rail. The rails of the 3° curve (test site #2) were exhibiting some signs of deterioration at the start of testing. Moderate shells, clearly visible in the photographs reproduced in Figure D.2, were present on both the high and low rails.

Both test curves were ground by Speno Rail Services Co. using their RMS1 grinder. The rails of the 6° curve were ground using a single pass of the grinder at 3 mph. The stone angles were set to produce a non-standard preventive grinding profile specified by NRC. Examination of the rails after grinding revealed that the intended rail profiles had not been achieved. The rails of the 3° curve were to be ground to the standard CP profiles #0 (for low rails) and #1 (for high rail) using four passes of the grinder at a speed of 3 mph. This process is similar to that conducted at approximately 25 MGT intervals in the usual corrective grinding cycle. Following the first grinding pass it was discovered that the stone settings for the high and low rails had been transposed. The stone settings were corrected for the second and third passes while the standard CP pattern #3 was used for both rails on the final pass to correct the damage caused by the first pass.

After grinding, the gauge corner cracking of the 6° curve's high rail was not significantly improved, due to a number of missing stones on the grinder. Figure D.3 shows the surface condition of this curve's high and low rails. The shelling of both the high and low rails of the 3° curve, illustrated in Figure D.4, was still noticeable following the 4 grinding passes which had removed material to an average depth of 0.050 inches.

Figures E.1 and E.2 compare the measured rail profiles before and after grinding for the high and low rails of the 6° curve, respectively. Figures E.3 and E.4 show similar plots for the rails of the 3° curve. These figures are plotted using an exaggerated scale of 2:1 in./in. horizontally and 3:1 in./in. vertically. In addition, the post-grinding curves have been offset from the pre-grinding curves for clarity.

Table F.1 summarizes the results of the rail grinding rate calculations for the two test sites. Corrugation measurements were taken along a short stretch (over 5 tie spacings, to the west of the wear measurement points), of the 3° degree curve. The results are given in Table F.2. These corrugations were completely removed by the grinding process.

Following the first site visit, each test site was ground regularly at approximately 2 month intervals (approximately every 9-10 MGT) using the initial rail grinding patterns.

The second site visit was conducted between June 9 and June 13, 1987. Approximately 40-45 MGT of traffic had travelled the rails since the start of the preventive grinding tests. Examination of the rail surface conditions indicated that the regular grinding had controlled shelling and plastic flow of the rails very effectively. The rail surface conditions at test sites #1 and #2 are shown in Figures D.5 and D.6, respectively. The frequent grinding had kept both high and low rails of the 6° curve in excellent condition and had totally eliminated the previously noted gauge corner cracking on the high rail. Conditions of the 3° curve had improved significantly since the last inspection. The grinding had eliminated gauge corner cracking on the high rail and had almost reached the root of fatigue cracking on the low rail.

The grinding patterns were modified for this set of tests to minimize metal removal from the field side of the high rail and the gauge side of the low rail and to ensure that the depth of metal removal at the gauge corner of the high rail and field corner of the low rail was approximately twice that of the centre region on the rail head. To achieve these new goals, the grinding stones on the field side of the high rail and gauge side of the low rail were lifted during grinding to prevent over-grinding in those regions. This new pattern was ground at the trial test site #3 at a speed of 10 mph and found to be satisfactory for application on the two primary test sites. Since the rails at the 6° curve were in such good condition, and therefore requiring little metal removal, a single grinding pass at 6 mph was performed. The 3° curve was ground with a single pass at 4 mph. All grinding during this site visit was performed by Loram Maintenance of Way, Inc.

Photographs taken of the rail head surfaces following grinding are reproduced in Figure D.7 for test site #1 and Figure D.8 for test site #2. Both rails of the 6° curve were found to be completely free from surface fatigue defects. The high rail of the 3° curve was similarly found to be defect free while the low rail still showed some signs of cracking. However, it was evident that the frequent grindings were slowly getting to the root of these cracks.

The third and final visit to the CP Rail preventive grinding test sites was made on August 13, 1987, exactly two months following the second visit. The total traffic volume since the start of testing had reached approximately 50-55 MGT. Figures D.9 and D.10 show photographs of the rails at test sites #1 and #2, respectively, taken immediately prior to grinding.

Figure D.9 shows the conditions of the high and low rails at test site #1, the 6° curve. The rails were in good condition, having only very slight snake skin cracks on the low rail and barely perceptible gauge corner cracks on the high rail. Some of the grinding facets were still readily visible from the previous grinding cycle.

Figure D.10 shows the condition of the high and low rails at test site #2, the 3° curve. The high rail had developed slight gauge corner shelling, while the low rail had some shelling in the centre regions of the rail head. It was felt that the cracks on the low rail were still propagating from the deeply rooted cracks which were present in the rail prior to the start of these tests in September 1986.

The rail grinding contractor at this occasion was Speno Rail Services Co. Grinding of the rails at the two primary test sites proceeded exactly as in the previous grinding cycle. The pattern used was designed to remove twice as much metal from the gauge corner of the high rail and field corner of the low rail as removed from the rail head's centre region while removing very little material from the field side of the high rail and gauge side of the low rail. A single grinding pass over the 6° curve was made at a speed of 6 mph and a single grinding pass at 4 mph was made over the 3° curve. The trial test site #3 was again ground at 10 mph and an additional grinding at 2 mph was carried out at the trial test site #4.

The condition of the rails at test sites #1 and #2 after grinding are shown in Figures D.11 and D.12, respectively. As the weather conditions throughout the tests was cool and wet, particularly during and after grinding measurements, the dye penetrant did not accentuate the surface fatigue cracking as effectively as in the previous site visits. Figure D.11 clearly illustrates the good condition of the rails at test site #1 following grinding. The previously noted snake skin cracking on the low rail was completely eliminated. Grinding of the rails at test site #2 resulted in the significantly improved rail head surface conditions as shown in Figure D.12. Some cracking was still visible on the low rail even though the depth of metal removal in the vicinity of these cracks was between 0.016 and 0.018 inches.

The grinding rate is presented in the form of line charts in Figures F.1 and F.2, showing the depth of metal removal against the wear gauge reading numbers (at 1/8 inch intervals across the rail head). Figure F.1 includes data from the high rails of the trial test site #4 and primary test sites #1 and #2, while Figure F.2 relates to the low rails of these test sites. These figures illustrate the grinding production and effort (in terms of depth of metal removed) across the rail head. The produced patterns are generally close to that intended at each test site, although some further refinement of the grinding effort at the field side of the high rail and gauge side of the low rail may be desirable.

By referring to Figure F.1 it is evident that at test site #2, the 3° curve at mile post 55.5, the depth of metal removal was somewhat lower than expected at reading positions 9, 10 and 11. This was due to broken grinding stones allocated to that zone of the rail head. The lower metal removal at this location is also reflected in Figure F.3, which is a graph of total area (volume per unit length) of metal removed plotted against speed of grinding. It should be noted that the sequence of grinding was in the direction of decreasing mile post. Figure F.4 is similar to Figure F.3 and relates to the low rails of the test sites. The amount of metal removal at the higher speeds of 4 and 6 mph is certainly of a magnitude that can be used effectively for preventive grinding. This would speed up the grinding process considerably as regular grinding operations normally proceed at speeds of 2 to 3 mph.

Further illustration of the amount of metal removal can be seen in Figures E.5 through E.10. Each figure shows a superimposed plot of pre- and post-grinding rail head profiles of the high and low rails at primary test sites #1 and #2 and at the trial test site #4.

3.2.2 BC Rail Preventive Grinding Test

The first set of tests were conducted on BC Rail's Chetwynd Subdivision over the period of September 16-18, 1986. Prior to grinding, a dye penetrant was applied to the rail heads at all test locations and photographs taken to record the rail head surface conditions. Figures D.13, D.14 and D.15 are reproductions of the photographs taken at test sites #1, #2 and #3 respectively. The high rail of the 6° curve (test site #1) had some cracking on the gauge corner while the low rail was in good condition. Both the tangent rails at test site #2 were in good shape. At the 3° curve (test site #3), the high rail displayed some cracking on the gauge corner and the low rail was free of surface fatigue defects.

All three test sites were ground by Loram Maintenance of Way, Inc. using single passes of their RGM-1 grinder at a constant speed of 2 mph. The grinding pattern used was intended to relieve the gauge corner, produce a 12 to 14 inch crown radius and remove material to an approximate depth of 0.003 inches during each grinding cycle. The grinder was configured to use 42 stones while grinding the profile of the 6° and 3° curves and 40 stones to grind the stretch of tangent track.

After grinding, the gauge corner cracking of the 6° curve's high rail were still present. Figure D.16 shows the surface condition of both the high and low rails at this location. The post-grinding condition of the tangent rails of test site #2 are illustrated in Figure D.17. The gauge corner cracking on the high rail of the 3° curve (test site #3) had disappeared following grinding as shown in Figure D.18.

The speed grinding test conducted during this site visit involved the grinding of tangent rails at three locations using the same grinding pattern employed for the preventive grinding tests reported above but varying the grinding speed. One pass grinding with 40 stones was carried out at 3 mph at test site #4, at 5 mph at test site #5, and at 8 mph at test site #6. Rail profiles were measured at each of these three locations both before and after grinding so that the amount of metal removed by grinding could be established.

The results of the rail profile measurements at all six test sites before and after grinding are given in Figures E.11 through E.21. Average radii of curvature of the expected contact band region (between the arrows) for each rail are also shown in the figures. These are identified as R_{pre} and R_{post} signifying pre-grinding and post-grinding radii of curvature, respectively. The plots are magnified to a scale of 2.5:1 in./in. in both the horizontal and vertical axes. This avoids any distortion of the rail profiles and makes visualization of the indicated radii easier.

The preventive grinding patterns were modified to some extent during the progress of this first set of tests. This may be the main reason for the deviation of the post-grinding radii of curvature from the originally intended values ranging between 12 and 14 inches. The indicated values (Figures E.11 through E.21) were typically in the range of 8 to 10 inches, with the exception of the high rails at Test Sites #1 and #3, which had post-grinding radii of curvature of 16.3 and 13.9 inches, respectively.

Tables F.3 and F.4 summarise the results of the rail grinding rates calculated from the rail profile measurements.

The results of the speed grinding tests are presented graphically in Figure F.7, which shows a plot of total volume of metal removed against speed of grinding. It should be noted that at test site #4, with a grinding speed of 3 mph, the grinding measurement included the west rail only. The results indicate a sharper drop in volume of metal removed at speeds greater than 5 miles per hour, when compared to volume of metal removed at lower speeds. The graph, however, indicates that for small amounts of metal removal (0.01 to 0.02 $\text{in.}^3/\text{in.}$) as is the case in preventive grinding, speeds of 5 to 6 mph can be utilized.

Following the first site visit, a cycle of preventive (maintenance) grinding had been carried out at the test sites in December of 1986. The rails were ground with the NRC preventive grinding pattern which was previously used during the first site visit. Traffic volume between the time of the first site visit and the December grinding was estimated to be between 4 and 5 MGT.

The second site visit was conducted between April 12 and 15, 1987. After approximately 6 MGT of traffic had travelled the rails since the last grinding cycle, the rail surface conditions at test site #1 (6° curve), test site #2 (tangent) and test site #3 (3° curve) were as shown in Figures D.19, D.20 and D.21, respectively.

The preventive grinding had been effective in maintaining the rails in good condition at test sites #2 and #3, namely the tangent section and the 3° curve. The high rail of test site #1 (6° curve), on the other hand, was found to have more extensive fatigue cracks than at the first site visit in September of 1986.

A new preventive grinding pattern was used to grind the two test curves at 3 mph, while skipping the tangent section in between. This new pattern is referenced as the NRC revised preventive grinding pattern. Inspection of the tangent track (at mile post 470.8) revealed no major cracks, and so the decision was made to leave the rails at this location unground until the next site visit. The grinding contractor was Loram Maintenance of Way, Inc.

Figures D.22 and D.23 are photographs of the rails at test site #1 and test site #3, respectively, taken after grinding and application of dye penetrant. As the section of tangent track (test site #2) was not ground, there are no post-grinding photographs corresponding to that location. It is evident from Figure D.22 that this grinding cycle had done little to remove the gauge corner cracking on the high rail of the 6° curve. The 3° curve (Figure D.23) was free of surface defects on both rails.

Speed grinding tests were conducted at the three test locations (#4, #5 and #6) used during the first site visit and one test location which was added during the second site visit (#4a). Each of these locations received a single grinding pass at speeds ranging between 4 and 10 mph. Test site #4 was ground at 4 mph, test site #4a at 6 mph, test site #5 at 8 mph, and test site #6 at 10 mph.

The results of rail profile measurements taken at each test site ground during the second site visit are presented in Figures E.22 through E.33. Each figure shows the profile of the rail head before and after grinding plotted to a magnified scale of 2.5:1 in./in. In addition, the radii of curvature of the rail head before and after grinding are indicated in each figure. These are identified as R_{pre} and R_{post} for the pre-grinding and post-grinding radii of curvature respectively. In order to have a constant base of reference for comparison of radii of curvature from one test period to the next, the radii were calculated over a 1.25 inch width at about the approximate centre of the rail head.

Tables F.5 and F.6 summarize the results of the rail grinding rate calculations.

The results of the speed grinding tests are presented graphically in Figure F.8, which shows a plot of total volume of metal removed against grinding speed. It can be seen that there is a sharp drop in the volume of metal removal when the grinder speed exceeds 4 miles per hour. However, this lower amount of metal removal is considered sufficient for preventive grinding. The results also indicate that the amount of metal removal was approximately constant between speeds of 6 and 10 miles per hour. While this finding is interesting and encouraging in terms of shorter track occupation time, it is important to consider a number of other factors before such grinding speeds can be implemented. Some of these factors include quality of grinding, in terms of uniformity over a long stretch of track, the ability of the grinder to sustain such grinding speeds over extended periods without costly breakdowns, and so on.

The second site visit concluded with a grinder endurance test. The plan was to try grinding at 10 miles per hour over a 10-mile stretch of tangent track (between mile posts 475.0 and 485.0). This test was prematurely ended at mile post 482.0 when it was discovered that the high speed of 10 miles per hour could not be maintained on small uphill grades (less than 1%) with pressure applied on the grinding stones. In addition, the combination of high speed, track grade and grinding pressure were resulting in heavy vibration of the grinding motors and mountings.

Following the second site visit, the test locations were ground in early August of 1987. Approximately 5 MGT of traffic had passed since the last grinding cycle. The high rails in the 6° curve (test site #1) and the 3° curve (test site #3) were ground at a speed of 3 mph with one pass of Loram's gauge relief pattern and one pass of the NRC revised preventive grinding pattern used during the second site visit. The low rails of these curves and the tangent rails of test site #2 were not ground at that time.

The third, and final site visit, was made between November 1 and 2, 1987. During the period since the previous grinding cycle the traffic was estimated to fall between 4 and 5 MGTs. Figures D.24, D.25 and D.26 show the surface condition of the rails prior to grinding at test sites #1, #2 and #3, respectively. At the 6° curve, depicted in Figure D.24, some cracking was observed near the gauge shoulder of the high rail while many fine cracks were visible in the centre and field zones of the low rail. Both tangent rails at test site #2, Figure D.25, had a small amount of fatigue cracking in the gauge zone. At the 3° curve, shown in Figure D.26, the high rail had some cracks on the gauge corner while no cracking was visible on the low rail.

Both curves received two grinder passes at 3 mph, the first with Loram's gauge relief pattern, the second with the NRC revised preventive grinding pattern. The tangent track at Test Site #2 received a single grinding pass at 3 mph using the NRC revised preventive grinding pattern.

The NRC revised preventive grinding pattern successfully removed the damaged material from the rail head at all three test locations. Figures D.27, D.28 and D.29 show the post-grinding conditions of the rails at the 6° curve, tangent section and the 3° curve, respectively.

Three test locations were used for the final speed grinding tests. Test site #4 was ground at 3 mph, test site #4a was ground at 6 mph, and test site #6 was ground at 9 mph. Each of these sites received a single grinding pass using the NRC revised preventive grinding pattern.

Results of the rail profile measurements at test sites #1, #2, #3, #4, #4a and #6 are presented in Figures E.34 through E.45, respectively. Each figure shows the rail head profile before and after grinding plotted to magnified scales of 2.5:1 in./in. horizontally and 9.5:1 in./in. vertically. The radii of curvature calculated over a 1.25 inch width centred on rail head surface ranged between a low of approximately 4 inches to a high of approximately 8.5 inches. Tables F.7 through F.18 summarize the radii and depth of cut results for each of these test sites.

The results of the speed grinding tests are presented graphically in Figures F.9 and F.10. Figure F.9 plots the average radial depth of cut against the grinding speed while Figure F.10 plots the amount of metal removal versus grinding speed. These results serve to reinforce the previously observed trend of decreasing metal removal as the grinder's forward speed is increased.

4.0 DISCUSSION

4.1 On Rail Grinding Performance

The normalized grinding depth (third column in Tables A.1 through A.11) indicates that grinding productivity varied quite considerably from site to site. There are a number of causes for the variations, such as:

- the type of grinding equipment
- the condition of the grinding equipment
- the number of grinding passes
- the rail conditions

Consistent ground rail profiles were not produced. Incorrect grinding settings and equipment malfunctions were two major contributors to this problem. A stricter quality control procedure, including a method for field validation of the ground rail contour, is necessary to ensure satisfactory results.

4.2 On Preventive Maintenance Grinding

The NRC preventive grinding pattern tries to compromise between two diverse requirements, one being the necessity of gauge contact for proper curve negotiation, and the other being the necessity to avoid heavy contact at the gauge corner to preserve the rail material at this location. The compromise will be reached if the grinding of the gauge corner can ensure that no contact is made at this location just after a grinding cycle, with slight contact developing just prior to the next grinding cycle. The main requirements for achieving this objective are that the amount of metal removal at the gauge corner must be at least twice as much as that at the centre of the rail head, and the ground gauge corner of the rail should match the profile of the wheel tread to flange transition more closely.

Generally speaking, the NRC preventive grinding pattern was effective in controlling the development and propagation of surface defects at the locations tested on BC Rail and CP Rail tracks. In most cases only very slight gauge corner cracking had developed on the high rails of the test curves between grinding cycles and was readily removed by the preventive grinding pattern. However, it was obvious from the condition of the BC Rail 6° curve test site during the second site visit that the particular combination of grinding cycle frequency and ground profile had not prevented rail deterioration as expected. This was most likely due to poor matching of the geometries of the wheel tread to flange transition with that of the rail head's gauge corner. Subsequent use of the NRC revised preventive grinding profile did result in improved surface conditions at this location.

A summary of the grinding performed during each visit to the CP Rail and BC Rail test sites is provided in Tables 4.1 and 4.2, respectively. The initial grinding of the 3° curve at the CP Rail test site #3 is representative of normal corrective grinding practice where rails are ground to standard CP profiles #0 (for high rails) and #1 (for low rails) at intervals of approximately 25 MGT. Specifically, material is removed to an average depth ranging between 0.040 and 0.050

inches using 4 passes of the grinder travelling at a low speed of between 2 and 3 mph. This will be considered a base case scenario against which the relative economy of the preventive grinding processes implemented in this study are evaluated in the discussion to follow.

Table 4.1: Summary of Preventive Grinding Tests on CP Rail

	Test 1		Test 2*		Test 3	
Site	Grinder Passes (inches)	Depth of Cut	Grinder Passes (inches)	Depth of Cut	Grinder Passes (inches)	Depth of Cut
1 (6° curve)	1 NRC (3 mph)	.006 high .005 low	1 NRC (6 mph)		1 NRC (6 mph)	.010 high .007 low
2 (3° curve)	4 CP(0,1) (3 mph)	.050 high .040 low	1 NRC (4 mph)		1 NRC (4 mph)	.009 high .008 low

* Post-grinding rail head profiles for test #2 not available.

Table 4.2: Summary of Preventive Grinding Tests on BC Rail

	Test 1		Test 2*		Test 3	
	Grinder Passes (inches)	Depth of Cut	Grinder Passes (inches)	Depth of Cut	Grinder Passes (inches)	Depth of Cut
1 (6° curve)	1 NRC (2 mph)	.015 high .016 low	1 NRC (3 mph)	.008 high .009 low	1 Relief (3 mph) 1 NRC (3 mph)	.015 high .010 low
2 (tangent)	1 NRC (2 mph)	.011 east .013 west			1 NRC (3 mph)	.014 east .014 west
3 (3° curve)	1 NRC (2 mph)	.012 high .016 low	1 NRC (3 mph)	.008 high .010 low	1 Relief (3 mph) 1 NRC (3 mph)	.015 high .009 low

* Tangent track not ground during second field test.

Preventive maintenance grinding of the CP Rail test sites was performed at intervals of approximately 10 MGT. As summarized in Table 4.1, all test rails were ground using an NRC preventive grinding pattern in a single grinding pass (with the exception of the base case previously discussed) and resulted in average depths of cut ranging between 0.005 and 0.010 inches. For the revised preventive grinding pattern used during Test 3 the average depth of metal removal across the high rails of both the 6° and 3° curves was approximately 0.010 inches while for both low rails it was about 0.008 inches. Over the 25 MGT base case interval this corresponds to 2.5 grinding passes where a total of approximately 0.025 inches and 0.020 inches of material is removed, on average, from the high and low rails, respectively. Therefore, this preventive grinding cycle controlled surface fatigue defects while using only 62% of the base case passes, removing less than 50% of the rail head material and proceeding at up to twice the speed used in corrective grinding.

A different preventive maintenance grinding cycle was applied at the BC Rail test sites. For this preventive grinding cycle, performed at roughly 5 MGT intervals, the average depth of cut ranged between 0.008 and 0.015 inches (see Table 4.2). The rails were ground to NRC preventive grinding profiles during the first two field tests using a single grinding pass while during the final test two passes were used to grind the curved sites. For the revised preventive grinding pattern used during the last test the average depth of metal removal per rail across the high rails of both the 6° and 3° curves was approximately 0.015 inches while for the low rails it was approximately 0.010 inches. Over the 25 MGT base case interval, this preventive cycle would apply 5 grinding passes (10 when double passes are used on curves) where material is removed to approximate depths of 0.050 inches on low rails and 0.075 inches on high rails. This corresponds to a 20% increase in the number of grinding passes (assuming single pass grinding) and an increase in the range of approximately 20 to 50 percent in metal removal when compared to the base case corrective grinding cycle. It should also be noted that all grinding proceeded within a range of speeds characteristic of corrective grinding (2 to 3 mph).

Comparison of the BC Rail test results with those from the CP Rail tests reveals that the preventive grinding cycle used on BC Rail resulted in the removal of roughly 50 percent more material from the high rails and approximately 20 percent more material from the low rails of both the 6° and 3° curves during the final grinding session. This is most certainly due to the much slower grinding speed used during the BC Rail tests than was used during the CP Rail tests.

It is evident, from the observations made during the preventive grinding tests on BC Rail and CP Rail tracks, that the combination of frequent grinding cycles together with the refined preventive grinding pattern was able to control the development and propagation of fatigue defects on the rail head surfaces of all test sites. The preventive grinding cycle as implemented at the CP Rail test sites was found to require the lowest number of grinding passes and removed less material from the rail head than both the base case corrective grinding cycle and the preventive cycle at 5 MGT intervals. Therefore, the 10 MGT preventive grinding cycle should prove to be more economical when compared to the other two.

A thorough economic evaluation of rail grinding programs would generally require examination of both the direct costs of operating a grinder, which would tend to decrease as the grinding cycle interval increases, and the secondary costs of maintenance (repairs to damaged rails, ties, vehicles, etc.) induced by the deteriorated rails, which would tend to increase with the interval between grindings. However, since it is widely acknowledged throughout the industry that rails must be ground to control damage of track infrastructure and rolling stock, and in this case the 10 MGT cycle requires less grinding effort and metal removal than the 25 MGT corrective cycle, comparison of the direct costs of operating a grinder does suffice.

This does not necessarily represent an optimum solution. Phase II of this research programme, as outlined in the introduction to this report, established that a preventive grinding cycle consisting of single grinding passes performed at 12 MGT intervals would be more effective than the use of double grinding passes at intervals of 18 MGT. The additional data obtained from this third phase of work would suggest that the optimum interval for a single pass grinding cycle lies somewhere between 10 and 18 MGT. A much larger number of tests with greater variation of pattern, frequency and grinding speeds than those undertaken here would be required to establish an optimum process.

Should preventive grinding continue to provide effective control of rail deterioration, and there is enough evidence to show that it will, then rail head wear may ultimately become the controlling criteria for replacement of rails. Therefore, it is important to have an approximate idea of how much the preventive grinding cycle contributes to the amount of metal lost from the head of the rail.

An estimate of the annual head loss was made by comparing the pre-grinding rail profile measurements at the CP Rail preventive grinding test sites #1 and #2 in June of 1987 with the pre-grinding rail profile measurements taken in August of 1987. The difference represents the amount of metal lost due to wear and one grinding cycle, over a two month period. Figures F.5 and F.6 show this metal loss graphically. Converting the amount of metal lost during this period to head loss results in an average head loss of 0.9% for the Algoma rails (CP test site #2) and 0.75% for the Japanese rails (CP test site #1). The amount of metal removed as a result of grinding in August translates to an average head loss of 0.5% at both test sites. Assuming that the amount of metal removed due to grinding was the same in June and August then the head loss as a result of wear only will be 0.4% and 0.25% for the Algoma and Japanese rails, respectively. Annual head loss values based on these figures are presented in Table 4.3.

Table 4.3: Annual Head Loss Estimates For CP Test Site #2

	Annual Rail Head Loss (%)		
Test Site No.	WEAR	GRINDING	TOTAL
1 (Superrail)	1.5	3.0	4.5
2 (Algoma)	2.4	3.0	5.4

The rail profile measurements taken in August showed that the high rail of CP test site #2, with accumulated tonnage of approximately 240 MGT, had the highest head loss at approximately 12 percent. Therefore based on the above annual head loss estimates it would take another 3 to 4 years, or approximately 180 to 240 MGT of traffic, before the head loss reaches 30-35 percent. In contrast, CP has had to replace rails on curves similar to that at test site #2 at an average accumulated tonnage of 212 MGT.

Although CP specifications currently allow a head loss of 35 percent, in practice this value is rarely reached, and rails are normally replaced at around 25 percent head loss. If full advantage is to be taken of good grinding practice and maintenance of rails, it is important to take advantage of the highest allowable head wear limits.

The results of a Finite Element Method analysis of rail stress in tangent track, recently conducted by CIGGT and summarized in Appendix G of this report, indicate that overall rail head stresses increase as the rail head cross-sectional area decreases due to metal removal on the rail head. Although these increased stress levels are not themselves likely to initiate surface fatigue cracking in curved track due to the relatively high rate of metal attrition at the rail head surface, they may play a significant role in the propagation of cracks once present. Thus, the increased stress levels induced by a reduction in rail head cross-sectional area may increase the severity of metal fatigue causing rail deterioration and require increased rail grinding effort to remove even more material. This scenario implies a synergistic relationship between contact stress and rail head internal stresses such that the severity and effort required to repair surface defects may increase with rail head loss. It is important to note, however, that significant differences in the worn profiles which are characteristic of tangent and curved track may lead to very different results. Further analysis of stress levels in rail with worn profiles characteristic of curved track would help to clarify these differences.

5.0 CONCLUSIONS

Regarding the assessment of rail grinding performance on CP Rail, the following conclusions are offered:

(a) Proportion of depth of metal removed which was within specifications was as follows:

Centre zone:	Grinder A 40 percent, Grinder B 39 percent
Gauge zone:	Grinder A 33 percent, Grinder B 36 percent
Field zone:	Grinder A 47 percent, Grinder B 73 percent

(b) The clearest observation with regard to points which fell outside the specified ranges concerned the centre zone grinding. For this zone Grinder B's metal removal was too high while Grinder A's was too little.

(c) A higher proportion of contact band radii of curvature of rails ground by Grinder B was within specification (37 percent for Grinder A versus 54 percent for Grinder B).

Observations made throughout the preventive maintenance grinding experiments, conducted on CP Rail and BC Rail tracks, support the following:

(a) Preventive grinding programs can effectively maintain rail head surfaces free of major fatigue defects. An optimum interval for a grinding cycle is likely to lie somewhere between 10 and 18 MGT for curves of up to 6°. In the limited test comparison with the 5 MGT preventive grinding cycle and the 25 MGT corrective cycle, the preventive grinding cycle conducted at 10 MGT intervals appears to be more economical in terms of both grinding effort and metal removal.

(b) To ensure effective control of fatigue cracks at sharp curves, the amount of metal removal on the gauge corner should be at least twice that of the centre region of the rail head. Smooth transitions from facet to facet on the gauge corner are critical if stress concentrations, and therefore accelerated wear, are to be avoided.

(c) The amount of rail head metal lost due to preventive grinding throughout the duration of testing did not appear to significantly reduce the useful life of the ground rails.

(d) It is strongly indicated that preventive grinding practice will significantly increase rail life. Rail head wear, rather than surface fatigue defects, may ultimately become the criteria controlling the replacement of rails.

However, further detailed examination of the effect of rail head metal loss on rail fatigue should be performed to establish appropriate wear limits.

(e) The speed grinding test results indicate that the amount of metal removed is essentially constant at speeds ranging between 6 and 10 mph and is sufficient in magnitude for preventive grinding.

6.0 RECOMMENDATIONS

Based upon the results of this study the following recommendations are provided:

(a) Stricter quality control procedures, including field verification of ground rail contours, should be used to ensure optimal rail conditions.

(b) The relationship between head loss and increased rail fatigue on curved track should be examined in detail.

7.0 REFERENCES

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3. Lamson, S.T., Roney, M.D. *CP Rail Grinding Field Manual*. CIGGT Report No. 86-30, Transport Canada Report No. TP-8174E, December 1986.

4. Kalousek, J., Lam, F. *Corrective and Preventive Rail Grinding - Evaluation of the Field Tests*. National Research Council Report No. TR-TM-012, March 1989.

APPENDIX A

CP RAIL GRINDING PERFORMANCE

DETAILS OF RAIL GRINDING EVALUATIONS

Table A.1: Evaluation of Grinding on CP Heron Bay Subdivision

Site Description		Zone	Average Grinding Depth Normalized to 1 Pass at 2.5 mph (in.)	Evaluation of Grinding Depth	Radius of Curvature of Contact Band Before/After (in.)	Evaluation of Radius of Curvature
1.1	Curve #1, high rail,	field	0.010	okay		
	115 lb/yd, 1982,	centre	0.006	okay		
	2 passes @ 2.5 mph	gauge	0.005	low	5.8	
		total head	0.007		4.5	low
1.2	Curve #1, low rail,	field	0.014	okay		
	1974, rail transposed 1981,	centre	0.010	okay		
	1 pass @ 2.5 mph	gauge	0.012	okay	4.3	
		total head	0.012		4.4	low
1.3	MP 16.8, low rail,	field	0.013	okay		
	1976,	centre	0.005	low		
	1 pass @ 2.5 mph	gauge	0.002	low	5.0	
		total head	0.007		4.8	low
1.4	MP 17.1, high rail,	field	0.009	low		
	3 passes @ 2.5 mph	centre	0.004	low		
		gauge	0.005	low	5.4	
		total head	0.006		4.2	low
1.5	MP 17.1, low rail,	field	0.005	low		
	3 passes @ 2.5 mph	centre	0.007	okay		
		gauge	0.008	okay	7.0	
		total head	0.007		4.8	low
1.6	MP 17.5, low rail,	field	0.004	low		
	3 passes @ 2.5 mph	centre	0.005	low		
		gauge	0.008	okay	8.2	
		total head	0.006		4.8	low

Table A.2: Evaluation of Grinding on CP Galt Subdivision

Site Description		Zone	Average Grinding Depth Normalized to 1 Pass at 2.5 mph (in.)	Evaluation of Grinding Depth	Radius of Curvature of Contact Band Before/After (in.)	Evaluation of Radius of Curvature
2.1	MP 23.7, high rail (south track),	field	0.026*	high		
	136 lb/yd, 1980,	centre	0.003*	low		
	1 pass @ 4 mph	gauge	0.019*	low	7.5	
		total head	0.014*		5.7	low
2.2	MP 23.7, low rail (south track),	field	0.014*	okay		
	136 lb/yd, 1980,	centre	0.013*	high		
	1 pass @ 4 mph	gauge	0.022*	high	10.0	
		total head	0.016*		8.7	okay
2.3	MP 20.2, high rail (east track),	field	0.013*	okay		
	1 pass @ 4 mph	centre	0.003*	low		
		gauge	0.013*	low	6.1	
		total head	0.008*		5.2	low
2.4	MP 20.2, low rail (east track),	field	0.026*	okay		
	1 pass @ 4 mph	centre	0.008*	okay		
		gauge	0.011*	okay	5.4	
		total head	0.014*		4.6	low

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* Grinding rate is linear with speed for a speed range of 2 to 3 mph, but for this evaluation, normalization of grinding rates at a speed of 4 mph was also assumed linear.

Table A.3: Evaluation of Grinding on CP Crowsnest Subdivision

Site Description	Zone	Average Grinding Depth Normalized to 1 Pass at 2.5 mph (in.)	Evaluation of Grinding Depth	Radius of Curvature of Contact Band Before/After (in.)	Evaluation of Radius of Curvature
3.1 Curve #1, high rail, 2 passes @ 2.5 mph	field	0.007	low		
	centre	0.006	okay		
	gauge	0.016	low	15.7	
	total head	0.011		20.3	high
3.2 Curve #1, low rail, 2 passes @ 2.5 mph	field	0.018	okay		
	centre	0.010	okay		
	gauge	0.010	okay	14.6	
	total head	0.012		11.7	okay
3.3 Curve #2, low rail, 2 passes @ 2.5 mph	field	0.023	okay		
	centre	0.013	high		
	gauge	0.012	okay	16.7	
	total head	0.015		7.0	low
3.4 Tangent, left rail, 2 passes @ 2.5 mph	field	0.012	okay		
	centre	0.012	high		
	gauge	0.017	okay	8.2	
	total head	0.014		6.9	low
3.5 Tangent, right rail, 2 passes @ 2.5 mph	field	0.012	okay		
	centre	0.010	okay		
	gauge	0.019	okay	10.6	
	total head	0.014		8.4	low
3.6 Curve #3, low rail, 2 passes @ 2.5 mph	field	0.013	okay		
	centre	0.008	okay		
	gauge	0.013	okay	11.0	
	total head	0.011		6.8	low
3.7 Curve #3, high rail, 2 passes @ 2.5 mph	field	0.010	okay		
	centre	0.013	high		
	gauge	0.011	low	8.0	
	total head	0.011		17.7	high
3.8 LH at Fording Coal Spur, high rail, 136 lb/yd, 2 passes @ 2.5 mph	field	0.013	okay		
	centre	0.018	high		
	gauge	0.022	okay	5.4	
	total head	0.019		8.6	okay

Table A.3 (cont'd): Evaluation of Grinding on CP Crowsnest Subdivision

Site Description		Zone	Average Grinding Depth Normalized to 1 Pass at 2.5 mph (in.)	Evaluation of Grinding Depth	Radius of Curvature of Contact Band Before/After (in.)	Evaluation of Radius of Curvature
3.9	LHC at Fording Coal Spur,	field	0.018	okay		
	low rail,	centre	0.014	high		
	2 passes @ 2.5 mph	gauge	0.020	high	8.3	
		total head	0.017		12.9	okay
3.10	RHC, MP 12.5,	field	0.015	okay		
	low rail, 132 lb/yd,	centre	0.007	okay		
	2 passes @ 2.5 mph	gauge	0.017	high	8.5	
		total head	0.013		11.5	okay
3.11	RHC, MP 12.5,	field	0.017	okay		
	high rail, 132 lb/yd,	centre	0.017	high		
	2 passes @ 2.5 mph	gauge	0.015	low	8.1	
		total head	0.016		10.1	okay
3.12	LHC, MP 11.5,	field	0.011	low		
	high rail, 115 lb/yd,	centre	0.010	okay		
	2 passes @ 2.5 mph	gauge	0.016	okay	7.1	
		total head	0.013		8.8	
3.13	LHC, MP 11.5,	field	0.021	high		
	high rail,	centre	0.016	high		
	2 passes @ 2.5 mph	gauge	0.016	low	6.8	
		total head	0.017		7.1	low
3.14	LHC, MP 7.1,	field	0.022	high		
	high rail, 115 lb/yd	centre	0.013	high		
	2 passes @ 2.5 mph	gauge	0.018	low	6.4	
		total head	0.017		4.3	low
3.15	LHC, MP 7.1,	field	0.009	low		
	low rail,	centre	0.012	okay		
	2 passes @ 2.5 mph	gauge	0.023	high	10.4	
		total head	0.016		9.6	
3.16	RHC, MP 6.9,	field	0.020	okay		
	high rail, 115 lb/yd,	centre	0.015	high		
	2 passes @ 2.5 mph	gauge	0.018	low	9.2	
		total head	0.017		10.4	okay

Table A.3 (cont'd): Evaluation of Grinding on CP Crowsnest Subdivision

Site Description	Zone	Average Grinding Depth Normalized to 1 Pass at 2.5 mph (in.)	Evaluation of Grinding Depth	Radius of Curvature of Contact Band Before/After (in.)	Evaluation of Radius of Curvature
3.17 RHC, MP 6.9,	field	0.006	low		
low rail, 115 lb/yd,	centre	0.007	okay		
2 passes @ 2.5 mph	gauge	0.023	high	12.2	
	total head	0.013		8.9	okay
3.18 LHC, MP 22,	field	0.009	low		
high rail, 132 lb/yd,	centre	0.014	high		
2 passes @ 2.5 mph	gauge	0.011	low	6.0	
	total head	0.011		10.8	okay
3.19 LHC, MP 22,	field	0.008	low		
low rail, 132 lb/yd,	centre	0.008	okay		
2 passes @ 2.5 mph	gauge	0.013	okay	8.3	
	total head	0.010		10.6	okay
3.20 RHC, MP 37.8,	field	0.011	okay		
high rail, 132 lb/yd,	centre	0.017	high		
2 passes @ 2.5 mph	gauge	0.017	low	5.1	
	total head	0.016		9.4	okay
3.21 RHC, MP 37.8,	field	0.017	okay		
low rail, 132 lb/yd,	centre	0.013	high		
2 passes @ 2.5 mph	gauge	0.019	high	10.8	
	total head	0.017		15.6	high
3.22 LHC, MP 38.0,	field	0.016	okay		
high rail, 136 lb/yd,	centre	0.018	high		
2 passes @ 2.5 mph	gauge	0.016	low	7.4	
	total head	0.017		12.0	okay
3.23 LHC, MP 38.0,	field	0.015	okay		
low rail, 136 lb/yd,	centre	0.014	high		
2 passes @ 2.5 mph	gauge	0.022	high	9.6	
	total head	0.018		7.0	low

Table A.4: Evaluation of Grinding on CP Cascade Subdivision

Site Description		Zone	Average Grinding Depth Normalized to 1 Pass at 2.5 mph (in.)	Evaluation of Grinding Depth	Radius of Curvature of Contact Band Before/After (in.)	Evaluation of Radius of Curvature
4.1	RHC, MP 40.1,	field	0.018	okay		
	high rail, 136 lb/yd,	centre	0.010	okay		
	chrome, 1977,	gauge	0.016	low	10.2	
	2 passes @ 2.5 mph	total head	0.014		8.7	okay
4.2	RHC, MP 40.1,	field	0.018	okay		
	low rail, 136 lb/yd	centre	0.012	okay		
	chrome, 1977,	gauge	0.010	okay	13.0	
	2 passes @ 2.5 mph	total head	0.013		11.9	okay
4.3	RHC, MP 39.9,	field	0.017	okay		
	high rail, 136 lb/yd,	centre	0.015	high		
	chrome, 1977,	gauge	0.022	okay	7.9	
	1 pass @ 2.5 mph	total head	0.018		9.0	okay
4.4	RHC, MP 39.9,	field	0.029	okay		
	low rail, 136 lb/yd,	centre	0.014	high		
	chrome, 1977,	gauge	0.010	okay	16.8	
	1 pass @ 2.5 mph	total head	0.016		10.4	okay
4.5	RHC, MP 57.9,	field	0.009	low		
	high rail, 136 lb/yd,	centre	0.018	high		
	chrome, 1981,	gauge	0.010	low	6.0	
	1 pass @ 2.5 mph	total head	0.012		6.6	low
4.6	RHC, MP 57.9,	field	0.012	okay		
	low rail, 136 lb/yd,	centre	0.011	okay		
	chrome, 1969,	gauge	0.005	low	10.0	
	1 pass @ 2.5 mph	total head	0.009		8.6	okay
4.7	LHC, MP 68.1,	field	0.016	okay		
	high rail, 136 lb/yd,	centre	0.013	high		
	chrome, 1980,	gauge	0.010	low	5.6	
	1 pass @ 2.5 mph	total head	0.013		7.9	low
4.8	LHC, MP 68.1,	field	0.026	okay		
	low rail, 136 lb/yd,	centre	0.016	high		
	chrome, 1980,	gauge	0.017	low	8.9	
	1 pass @ 2.5 mph	total head	0.018		12.0	okay

Table A.4 (cont'd): Evaluation of Grinding on CP Cascade Subdivision

Site Description		Zone	Average Grinding Depth Normalized to 1 Pass at 2.5 mph (in.)	Evaluation of Grinding Depth	Radius of Curvature of Contact Band Before/After (in.)	Evaluation of Radius of Curvature
4.9	LHC, MP 68.8,	field	0.024	high		
	high rail, 136 lb/yd,	centre	0.023	high		
	chrome, 1980,	gauge	0.023	okay	7.0	
	1 pass @ 2.5 mph	total head	0.023		12.5	okay
4.10	LHC, MP 68.8,	field	0.020	okay		
	low rail, 136 lb/yd	centre	0.008	okay		
	chrome, 1984,	gauge	0.010	okay	7.0	
	1 pass @ 2.5 mph	total head	0.011		7.0	low

Table A.5: Evaluation of Grinding on CP Heron Bay Subdivision

Site Description		Zone	Average Grinding Depth Normalized to 1 Pass at 2.5 mph (in.)	Evaluation of Grinding Depth	Radius of Curvature of Contact Band Before/After (in.)	Evaluation of Radius of Curvature
5.1	LHC, MP 76.8,	field	0.027	high		
	high rail, 136 lb/yd,	centre	<0.001	low		
	chrome, 1978,	gauge	0.010	low	5.0	
	2 passes @ 2.5 mph	total head	0.011		5.1	low
5.2	LHC, MP 76.8,	field	0.011	low		
	low rail, 136 lb/yd	centre	0.003	low		
	chrome, 1978,	gauge	0.005	low	12.2	
	2 passes @ 2.5 mph	total head	0.006		8.6	okay
5.3	RHC, MP 77.75,	field	0.024	high		
	high rail, 136 lb/yd,	centre	0.002	low		
	chrome,	gauge	0.007	low	4.6	
	2 passes @ 2.5 mph	total head	0.006		3.8	low
5.4	LHC, MP 77.45,	field	0.011	okay		
	high rail, 136 lb/yd,	centre	<0.001	low		
	chrome, 1978,	gauge	0.009	low	7.4	
	2 passes @ 2.5 mph	total head	0.008		7.4	low
5.5	RHC, MP 77.30,	field	0.010	low		
	low rail, 136 lb/yd,	centre	0.002	low		
	chrome, 1978,	gauge	0.008	okay	23.4	
	2 passes @ 2.5 mph	total head	0.006		12.8	okay

Table A.6: Evaluation of Grinding on CP Kaminitiquia Subdivision

Site Description		Zone	Average Grinding Depth Normalized to 1 Pass at 2.5 mph (in.)	Evaluation of Grinding Depth	Radius of Curvature of Contact Band Before/After (in.)	Evaluation of Radius of Curvature
6.1	RHC, MP 80.7,	field	0.013	okay		
	high rail, 136 lb/yd,	centre	<0.018	high		
	Algoma CC, 1985,	gauge	0.034	okay	4.4	
	1 pass @ 3 mph	total head	0.020		4.3	low
6.2	RHC, MP 80.7,	field	0.034	okay		
	low rail, 136 lb/yd	centre	0.008	okay		
	Algoma CC, 1985,	gauge	0.018	high	7.2	
	1 pass @ 3 mph	total head	0.018		4.1	low

Table A.7: Evaluation of Grinding on CP Ignace Subdivision

Site Description		Zone	Average Grinding Depth Normalized to 1 Pass at 2.5 mph (in.)	Evaluation of Grinding Depth	Radius of Curvature of Contact Band Before/After (in.)	Evaluation of Radius of Curvature
7.1	RHC, MP 4.2,	field	0.018	okay		
	high rail, 115 lb/yd,	centre	0.023	high		
	Algoma CC, 1970,	gauge	0.051	high	7.8	
	1 pass @ 2.5 mph	total head	0.029		6.5	low
7.2	RHC, MP 4.2,	field	0.021	okay		
	low rail, 115 lb/yd	centre	0.011	okay		
	Algoma CC, 1970,	gauge	0.036	high	10.1	
	1 pass @ 2.5 mph	total head	0.020		8.8	okay
7.3	RHC, MP 4.3,	field	0.032	high		
	high rail, 115 lb/yd,	centre	0.023	high		
	Algoma CC, 1970,	gauge	0.041	high	9.4	
	1 pass @ 2.5 mph	total head	0.030		6.0	low
7.4	RHC, MP 4.3,	field	0.034	okay		
	low rail, 115 lb/yd,	centre	0.013	high		
	Algoma CC, 1970,	gauge	0.035	high	11.4	
	1 pass @ 2.5 mph	total head	0.025		7.8	low
7.5	LHC, MP 69.8,	field	0.012	okay		
	high rail, 115 lb/yd,	centre	0.019	high		
	Algoma CC, 1978,	gauge	0.031	okay	5.8	
	1 pass @ 2.5 mph	total head	0.020		4.1	low
7.6	LHC, MP 69.8,	field	0.024	okay		
	low rail, 115 lb/yd,	centre	0.008	okay		
	Algoma CC, 1978,	gauge	0.023	high	10.4	
	1 pass @ 2.5 mph	total head	0.016		8.9	okay

Table A.8: Evaluation of Grinding on CP Brooks Subdivision

Site Description		Zone	Average Grinding Depth Normalized to 1 Pass at 2.5 mph (in.)	Evaluation of Grinding Depth	Radius of Curvature of Contact Band Before/After (in.)	Evaluation of Radius of Curvature
8.1	1° LHC, MP 1.0,	field	0.009	low		
	high rail, 115 lb/yd,	centre	0.006	okay		
	Algoma, 1975,	gauge	0.009	low	13.5	
	1 pass @ 2.5 mph	total head	0.007		8.3	okay
8.2	2° LHC, MP 15.0,	field	0.020	okay		
	low rail, 115 lb/yd	centre	0.011	okay		
	Algoma, 1980,	gauge	0.008	okay	10.5	
	1 pass @ 3 mph	total head	0.012		7.9	low
8.3	2° LHC, MP 15.0,	field	0.017	okay		
	high rail, 115 lb/yd,	centre	0.008	okay		
	Algoma, 1980,	gauge	0.010	low	6.1	
	1 pass @ 3 mph	total head	0.010		4.3	low
8.4	1° RHC, MP 65.6,	field	0.008	low		
	low rail, 115 lb/yd,	centre	0.004	low		
	Algoma, 1974,	gauge	0.012	okay	9.0	
	1 pass @ 3 mph	total head	0.007		10.1	okay
8.5	1° LHC, MP 65.6,	field	0.026	high		
	high rail, 115 lb/yd,	centre	0.002	low		
	Algoma, 1974,	gauge	0.020	okay	8.1	
	1 pass @ 3 mph	total head	0.013		8.1	okay
8.6	3° RHC, MP 71.7,	field	0.008	low		
	low rail, 115 lb/yd,	centre	0.007	okay		
	Algoma, 1974,	gauge	0.007	low	10.4	
	1 pass @ 2.5 mph	total head	0.007		10.0	okay
8.7	3° LHC, MP 71.7,	field	0.017	okay		
	high rail, 115 lb/yd,	centre	0.021	high		
	Algoma, 1974,	gauge	0.031	okay	5.7	
	1 pass @ 2.5 mph	total head	0.023		6.3	low

Table A.8 (cont'd): Evaluation of Grinding on CP Brooks Subdivision

Site Description	Zone	Average Grinding Depth Normalized to 1 Pass at 2.5 mph (in.)	Evaluation of Grinding Depth	Radius of Curvature of Contact Band Before/After (in.)	Evaluation of Radius of Curvature
8.8 Tangent, MP 71.5, north rail, 115 lb/yd, Algoma, 1974, 1 pass @ 4 mph	field	0.013*	high		
	centre	0.003*	low		
	gauge	0.006*	low	8.6	
	total head	0.006*		8.8	low
8.9 Tangent, MP 71.5, south rail, 115 lb/yd 1 pass @ 4 mph	field	0.013*	high		
	centre	0.008*	okay		
	gauge	0.013*	low	11.3	
	total head	0.011*		11.4	okay

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* Grinding rate is linear with speed for a speed range of 2 to 3 mph, but for this evaluation, normalization of grinding rates at a speed of 4 mph was also assumed linear.

Table A.9: Evaluation of Grinding on CP Brooks Subdivision

Site Description		Zone	Average Grinding Depth Normalized to 1 Pass at 2.5 mph (in.)	Evaluation of Grinding Depth	Radius of Curvature of Contact Band Before/After (in.)	Evaluation of Radius of Curvature
9.1	3° C, low rail,	field	0.014	okay		
	115 lb/yd,	centre	0.006	okay		
	Algoma, 1975,	gauge	0.006	low	11.2	
	2 passes @ 2.5 mph	total head	0.009		8.2	
9.2	3° C, high rail,	field	0.018	okay		
	115 lb/yd,	centre	0.007	okay		
	Algoma, 1975,	gauge	0.010	low	7.3	
	2 passes @ 2.5 mph	total head	0.011		6.4	low

APPENDIX B

CP RAIL GRINDING PERFORMANCE

DETAILS OF RAIL GRINDING RATES

Table B.1: Rail Grinding Rates for CP Heron Bay Subdivision

Site Description		Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length ($in.^3$)
1.1	Curve #1, high rail, 115 lb/yd, 1982, 2 passes @ 2.5 mph	field	6	0.019	
		centre	7	0.012	
		gauge	5	0.010	
		total head	18	0.014	0.032
1.2	Curve #1, low rail, 1974, rail transposed 1981, 1 pass @ 2.5 mph	field	6	0.014	
		centre	7	0.010	
		gauge	4	0.012	
		total head	17	0.012	0.026
1.3	MP 16.8, low rail, 1976, 1 pass @ 2.5 mph	field	7	0.013	
		centre	7	0.005	
		gauge	6	0.002	
		total head	20	0.007	0.017
1.4	MP 17.1, high rail, 3 passes @ 2.5 mph	field	7	0.026	
		centre	7	0.011	
		gauge	5	0.016	
		total head	19	0.018	0.042
1.5	MP 17.1, low rail, 3 passes @ 2.5 mph	field	7	0.016	
		centre	7	0.022	
		gauge	6	0.025	
		total head	20	0.021	0.052
1.6	MP 17.5, low rail, 3 passes @ 2.5 mph	field	7	0.013	
		centre	7	0.014	
		gauge	6	0.025	
		total head	20	0.017	0.043

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table B.2: Rail Grinding Rates for Test Site #2, CP Galt Subdivision

Site Description		Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{3})
2.1	MP 23.7, high rail (south track), 136 lb/yd, 1980, 1 pass @ 4 mph	field	5	0.016	
		centre	7	0.002	
		gauge	5	0.012	
		total head	17	0.009	0.019
2.2	MP 23.7, low rail (south track), 136 lb/yd, 1980, 1 pass @ 4 mph	field	5	0.009	
		centre	7	0.008	
		gauge	5	0.014	
		total head	17	0.010	0.021
2.3	MP 20.2, high rail (east track), 1 pass @ 4 mph	field	3	0.008	
		centre	7	0.002	
		gauge	6	0.008	
		total head	16	0.005	0.010
2.4	MP 20.2, low rail (east track), 1 pass @ 4 mph	field	5	0.016	
		centre	7	0.005	
		gauge	6	0.007	
		total head	18	0.009	0.020

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table B.3: Rail Grinding Rates for Test Site #3, CP Crowsnest Subdivision

Site Description		Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{3})
3.1	Curve #1, high rail, 2 passes @ 2.5 mph	field	5	0.015	
		centre	7	0.011	
		gauge	10	0.032	
		total head	22	0.022	0.059
3.2	Curve #1, low rail, 2 passes @ 2.5 mph	field	5	0.035	
		centre	7	0.020	
		gauge	10	0.020	
		total head	22	0.024	0.065
3.3	Curve #2, low rail, 2 passes @ 2.5 mph	field	5	0.047	
		centre	7	0.026	
		gauge	8	0.023	
		total head	20	0.030	0.075
3.4	Tangent, left rail, 2 passes @ 2.5 mph	field	5	0.024	
		centre	7	0.025	
		gauge	10	0.033	
		total head	22	0.029	0.078
3.5	Tangent, right rail, 2 passes @ 2.5 mph	field	5	0.024	
		centre	7	0.021	
		gauge	9	0.037	
		total head	21	0.029	0.075
3.6	Curve #3, low rail, 2 passes @ 2.5 mph	field	5	0.026	
		centre	7	0.016	
		gauge	9	0.025	
		total head	21	0.022	0.059
3.7	Curve #3, high rail, 2 passes @ 2.5 mph	field	5	0.019	
		centre	7	0.026	
		gauge	9	0.021	
		total head	21	0.022	0.059
3.8	LH at Fording Coal Spur, high rail, 136 lb/yd, 2 passes @ 2.5 mph	field	5	0.026	
		centre	7	0.036	
		gauge	10	0.044	
		total head	22	0.037	0.103

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table B.3 (cont'd): Rail Grinding Rates for Test Site #3, CP Croswnest Subdivision

Site Description	Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{3})
3.9 LHC at Fording Coal Spur,	field	5	0.035	
low rail,	centre	7	0.029	
2 passes @ 2.5 mph	gauge	8	0.040	
	total head	20	0.035	0.087
3.10 RHC, MP 12.5,	field	5	0.031	
low rail, 132 lb/yd,	centre	7	0.015	
2 passes @ 2.5 mph	gauge	8	0.033	
	total head	20	0.026	0.065
3.11 RHC, MP 12.5,	field	5	0.034	
high rail, 132 lb/yd,	centre	7	0.033	
2 passes @ 2.5 mph	gauge	9	0.031	
	total head	21	0.032	0.085
3.12 LHC, MP 11.5,	field	5	0.022	
high rail, 115 lb/yd,	centre	7	0.019	
2 passes @ 2.5 mph	gauge	9	0.033	
	total head	21	0.026	0.067
3.13 LHC, MP 11.5,	field	5	0.043	
high rail,	centre	6	0.031	
2 passes @ 2.5 mph	gauge	7	0.032	
	total head	18	0.035	0.078
3.14 LHC, MP 7.1,	field	5	0.044	
high rail, 115 lb/yd	centre	7	0.026	
2 passes @ 2.5 mph	gauge	5	0.036	
	total head	17	0.034	0.073
3.15 LHC, MP 7.1,	field	5	0.017	
low rail,	centre	7	0.023	
2 passes @ 2.5 mph	gauge	9	0.045	
	total head	21	0.031	.082
3.16 RHC, MP 6.9,	field	5	0.040	
high rail, 115 lb/yd,	centre	7	0.030	
2 passes @ 2.5 mph	gauge	7	0.036	
	total head	19	0.035	.082

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table B.3 (cont'd): Rail Grinding Rates for Test Site #3, CP Crowsnest Subdivision

Site Description	Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{3})
3.17 RHC, MP 6.9, low rail, 115 lb/yd, 2 passes @ 2.5 mph	field	5	0.011	
	centre	7	0.013	
	gauge	9	0.046	
	total head	21	0.027	0.071
3.18 LHC, MP 22, high rail, 132 lb/yd, 2 passes @ 2.5 mph	field	5	0.018	
	centre	7	0.027	
	gauge	9	0.022	
	total head	21	0.023	0.060
3.19 LHC, MP 22, low rail, 132 lb/yd, 2 passes @ 2.5 mph	field	5	0.016	
	centre	7	0.016	
	gauge	9	0.026	
	total head	21	0.020	0.053
3.20 RHC, MP 37.8, high rail, 132 lb/yd, 2 passes @ 2.5 mph	field	5	0.022	
	centre	7	0.035	
	gauge	9	0.035	
	total head	21	0.032	0.083
3.21 RHC, MP 37.8, low rail, 132 lb/yd, 2 passes @ 2.5 mph	field	5	0.035	
	centre	7	0.026	
	gauge	8	0.039	
	total head	20	0.033	0.083
3.22 LHC, MP 38.0, high rail, 136 lb/yd, 2 passes @ 2.5 mph	field	5	0.031	
	centre	7	0.035	
	gauge	8	0.033	
	total head	20	0.033	0.083
3.23 LHC, MP 38.0, low rail, 136 lb/yd, 2 passes @ 2.5 mph	field	4	0.030	
	centre	7	0.028	
	gauge	9	0.044	
	total head	20	0.035	0.089

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table B.4: Rail Grinding Rates for Test Site #4, Cascade Subdivision

Site Description	Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{3})
4.1 RHC, MP 40.1,	field	5	0.037	
high rail, 136 lb/yd,	centre	7	0.019	
chrome, 1977,	gauge	8	0.031	
2 passes @ 2.5 mph	total head	20	0.028	0.071
4.2 RHC, MP 40.1,	field	4	0.037	
low rail, 136 lb/yd	centre	6	0.025	
chrome, 1977,	gauge	4	0.020	
2 passes @ 2.5 mph	total head	14	0.027	0.047
4.3 RHC, MP 39.9,	field	5	0.017	
high rail, 136 lb/yd,	centre	7	0.015	
chrome, 1977,	gauge	8	0.022	
1 pass @ 2.5 mph	total head	20	0.018	0.045
4.4 RHC, MP 39.9,	field	5	0.029	
low rail, 136 lb/yd,	centre	7	0.014	
chrome, 1977,	gauge	8	0.010	
1 pass @ 2.5 mph	total head	20	0.016	0.040
4.5 RHC, MP 57.9,	field	5	0.009	
high rail, 136 lb/yd,	centre	7	0.018	
chrome, 1981,	gauge	8	0.010	
1 pass @ 2.5 mph	total head	20	0.012	0.031
4.6 RHC, MP 57.9,	field	5	0.012	
low rail, 136 lb/yd,	centre	7	0.011	
chrome, 1969,	gauge	8	0.005	
1 pass @ 2.5 mph	total head	20	0.009	0.022
4.7 LHC, MP 68.1,	field	4	0.016	
high rail, 136 lb/yd,	centre	7	0.013	
chrome, 1980,	gauge	8	0.010	
1 pass @ 2.5 mph	total head	19	0.013	0.030
4.8 LHC, MP 68.1,	field	4	0.026	
low rail, 136 lb/yd,	centre	7	0.016	
chrome, 1980,	gauge	8	0.017	
1 pass @ 2.5 mph	total head	19	0.018	0.044

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table B.4 (cont'd): Rail Grinding Rates for Test Site #4, CP Cascade Subdivision

Site Description		Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{3})
4.9	LHC, MP 68.8,	field	4	.024	
	high rail, 136 lb/yd,	centre	7	.023	
	chrome, 1980,	gauge	8	.023	
	1 pass @ 2.5 mph	total head	19	.023	.055
4.10	LHC, MP 68.8,	field	3	.020	
	low rail, 136 lb/yd	centre	7	.008	
	chrome, 1984,	gauge	8	.010	
	1 pass @ 2.5 mph	total head	18	.011	.025

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table B.5: Rail Grinding Rates for Test Site #5, CP Heron Bay Subdivision

Site Description		Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{3})
5.1	LHC, MP 76.8,	field	5	0.053	
	high rail, 136 lb/yd,	centre	7	0.002	
	chrome, 1978,	gauge	7	0.020	
	2 passes @ 2.5 mph	total head	19	0.022	0.052
5.2	LHC, MP 76.8,	field	5	0.022	
	low rail, 136 lb/yd	centre	7	0.006	
	chrome, 1978,	gauge	9	0.011	
	2 passes @ 2.5 mph	total head	21	0.012	0.032
5.3	RHC, MP 77.75,	field	5	0.047	
	high rail, 136 lb/yd,	centre	4	0.004	
	chrome,	gauge	5	0.014	
	2 passes @ 2.5 mph	total head	14	0.023	0.040
5.4	LHC, MP 77.45,	field	5	0.023	
	high rail, 136 lb/yd,	centre	2	0.002	
	chrome, 1978,	gauge	4	0.017	
	2 passes @ 2.5 mph	total head	11	0.017	0.023
5.5	RHC, MP 77.30,	field	5	0.019	
	low rail, 136 lb/yd,	centre	7	0.005	
	chrome, 1978,	gauge	8	0.016	
	2 passes @ 2.5 mph	total head	20	0.013	0.032

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table B.6: Rail Grinding Rates for Test Site #6, CP Kaminitiquia Subdivision

Site Description		Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{3})
6.1	RHC, MP 80.7, high rail, 136 lb/yd, Algoma CC, 1985, 1 pass @ 3 mph	field	7	0.011	0.009
		centre	11	0.015	0.018
		gauge	6	0.028	0.019
		total head	22	0.017	0.046
6.2	RHC, MP 80.7, low rail, 136 lb/yd Algoma CC, 1985, 1 pass @ 3 mph	field	7	0.028	0.023
		centre	11	0.007	0.008
		gauge	5	0.015	0.009
		total head	21	0.015	0.040

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table B.7: Rail Grinding Rates for Test Site #7, CP Ignace Subdivision

Site Description		Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{2})
7.1	RHC, MP 4.2,	field	6	0.018	0.012
	high rail, 115 lb/yd,	centre	11	0.023	0.028
	Algoma CC, 1970,	gauge	6	0.051	0.033
	1 pass @ 2.5 mph	total head	21	0.029	0.073
7.2	RHC, MP 4.2,	field	8	0.021	0.018
	low rail, 115 lb/yd	centre	11	0.011	0.013
	Algoma CC, 1970,	gauge	5	0.028	0.019
	1 pass @ 2.5 mph	total head	22	0.020	0.050
7.3	RHC, MP 4.3,	field	4	0.032	0.012
	high rail, 115 lb/yd,	centre	11	0.023	0.028
	Algoma CC, 1970,	gauge	6	0.041	0.027
	1 pass @ 2.5 mph	total head	19	0.030	0.067
7.4	RHC, MP 4.3,	field	7	0.034	0.025
	low rail, 115 lb/yd,	centre	11	0.013	0.017
	Algoma CC, 1970,	gauge	5	0.035	0.018
	1 pass @ 2.5 mph	total head	21	0.025	0.060
7.5	LHC, MP 69.8,	field	5	0.012	0.006
	high rail, 115 lb/yd,	centre	11	0.019	0.023
	Algoma CC, 1978,	gauge	6	0.031	0.018
	1 pass @ 2.5 mph	total head	20	0.020	0.047
7.6	LHC, MP 69.8,	field	6	0.024	0.016
	low rail, 115 lb/yd,	centre	11	0.008	0.009
	Algoma CC, 1978,	gauge	5	0.023	0.012
	1 pass @ 2.5 mph	total head	20	0.016	0.037

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table B.8: Rail Grinding Rates for Test Site #8, CP Brooks Subdivision

Site Description		Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{3})
8.1	1° LHC, MP 1.0,	field	5	0.009	0.005
	high rail, 115 lb/yd,	centre	11	0.006	0.007
	Algoma, 1975,	gauge	6	0.009	0.005
	1 pass @ 2.5 mph	total head	20	0.007	0.017
8.2	2° LHC, MP 15.0,	field	6	0.017	0.011
	low rail, 115 lb/yd	centre	10	0.009	0.010
	Algoma, 1980,	gauge	6	0.007	0.004
	1 pass @ 3 mph	total head	20	0.010	0.024
8.3	2° LHC, MP 15.0,	field	5	0.014	0.007
	high rail, 115 lb/yd,	centre	11	0.007	0.008
	Algoma, 1980,	gauge	6	0.008	0.005
	1 pass @ 3 mph	total head	20	0.008	0.020
8.4	1° RHC, MP 65.6,	field	6	0.007	0.004
	low rail, 115 lb/yd,	centre	11	0.003	0.004
	Algoma, 1974,	gauge	7	0.010	0.008
	1 pass @ 3 mph	total head	22	0.006	0.016
8.5	1° LHC, MP 65.6,	field	5	0.022	0.011
	high rail, 115 lb/yd,	centre	11	0.002	0.002
	Algoma, 1974,	gauge	6	0.017	0.010
	1 pass @ 3 mph	total head	20	0.011	0.023
8.6	3° RHC, MP 71.7,	field	6	0.008	0.005
	low rail, 115 lb/yd,	centre	10	0.007	0.008
	Algoma, 1974,	gauge	7	0.007	0.005
	1 pass @ 2.5 mph	total head	21	0.007	0.018
8.7	3° LHC, MP 71.7,	field	5	0.017	0.009
	high rail, 115 lb/yd,	centre	9	0.021	0.021
	Algoma, 1974,	gauge	5	0.031	0.017
	1 pass @ 2.5 mph	total head	17	0.023	0.047

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table B.8 (cont'd): Rail Grinding Rates for Test Site #8, CP Brooks Subdivision

Site Description		Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{3})
8.8	Tangent, MP 71.5,	field	5	0.008	0.004
	north rail, 115 lb/yd,	centre	10	0.002	0.002
	Algoma, 1974,	gauge	5	0.004	0.002
	1 pass @ 4 mph	total head	18	0.004	0.007
8.9	Tangent, MP 71.5,	field	6	0.008	0.005
	south rail, 115 lb/yd	centre	10	0.005	0.006
	1 pass @ 4 mph	gauge	6	0.008	0.005
		total head	20	0.007	0.016

---

* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table B.9: Rail Grinding Rates for Test Site #9, CP Brooks Subdivision

Site Description		Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{3})
9.1	3° C, low rail,	field	8	0.028	0.023
	115 lb/yd,	centre	10	0.013	0.014
	Algoma, 1975,	gauge	6	0.013	0.008
	2 passes @ 2.5 mph	total head	22	0.018	0.045
9.2	3° C, high rail,	field	6	0.032	0.021
	115 lb/yd,	centre	10	0.015	0.017
	Algoma, 1975,	gauge	6	0.020	0.012
	2 passes @ 2.5 mph	total head	20	0.022	0.050

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table B.10: Rail Grinding Rates for Test Site #10, Cranbrook Subdivision

Site Description	Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{3})
10.1 2° LHC, MP 59.8, low rail, 132 lb/yd, Algoma, 1971, 1 pass @ 1.5 mph	field	7	0.019	0.014
	centre	10	0.021	0.023
	gauge	6	0.014	0.009
	total head	21	0.018	0.046
10.2 2° LHC, MP 59.8, high rail, 136 lb/yd, 1985, 1 pass @ 1.5 mph	field	6	0.039	0.025
	centre	10	0.028	0.031
	gauge	6	0.032	0.020
	total head	20	0.032	0.076

---

* A number of depth readings overlap at the field/centre and centre/gauge boundaries.

Table B.11: Rail Grinding Rates for Test Site #11, Cranbrook Subdivision

Site Description		Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed per Inch of Rail Length (in.^{2})
11.1	6° RHC, MP 66.5,	field	5	0.022	0.010
	high rail, 132 lb/yd,	centre	11	0.031	0.038
	Algoma, 1972,	gauge	5	0.036	0.018
	2 passes @ 2.5 mph	total head	19	0.030	0.066
11.2	6° RHC, MP 66.5,	field	8	0.026	0.023
	low rail, 132 lb/yd,	centre	10	0.024	0.026
	Algoma, 1972,	gauge	6	0.049	0.030
	2 passes @ 2.5 mph	total head	22	0.031	0.079

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

APPENDIX C

CP RAIL GRINDING PERFORMANCE

DETAILS OF RAIL HEAD PROFILES

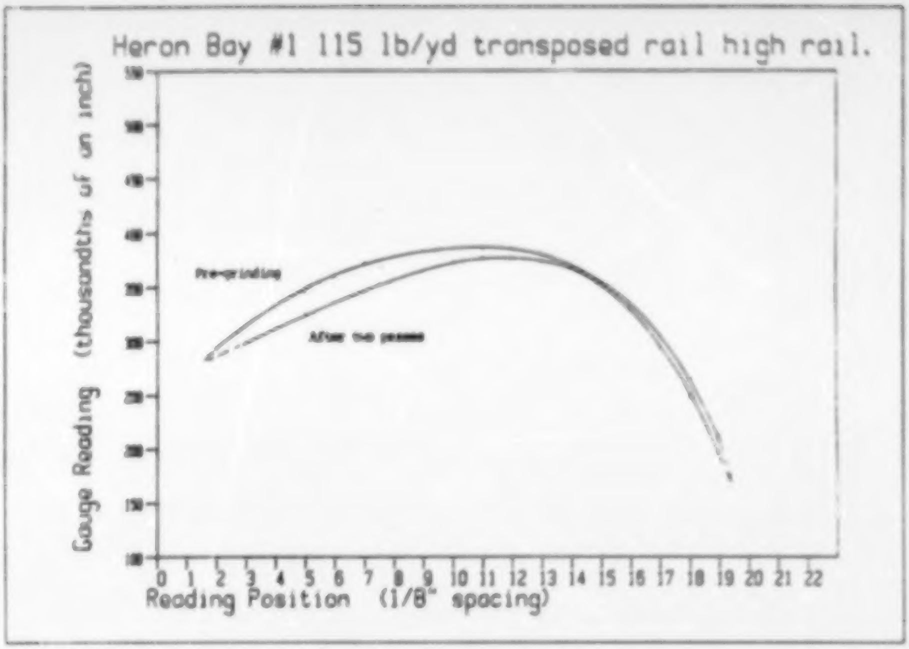


Figure C.1: Measured rail head profiles at test site 1.1 before and after grinding

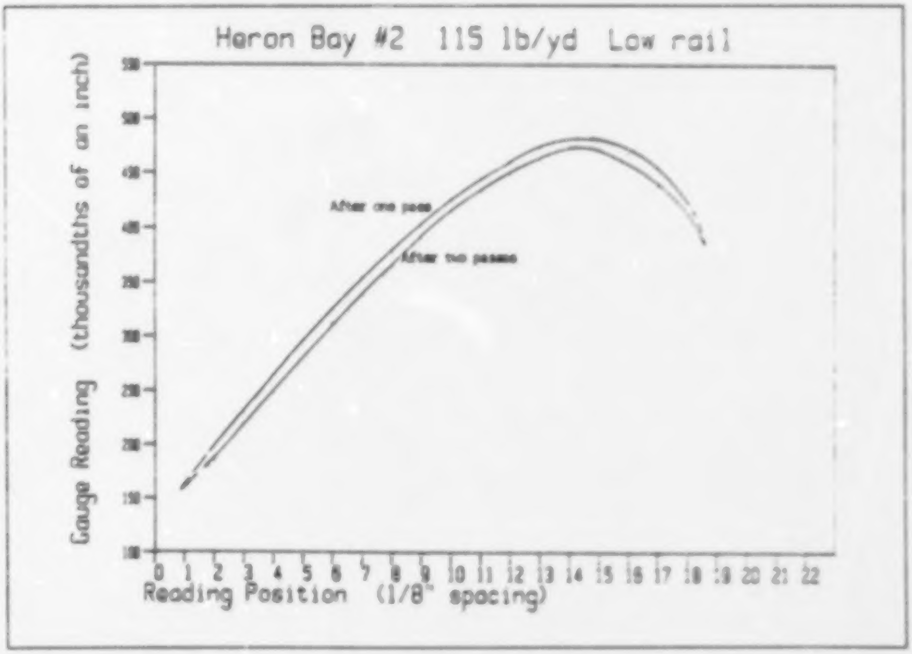


Figure C.2: Measured rail head profiles at test site 1.2 before and after grinding

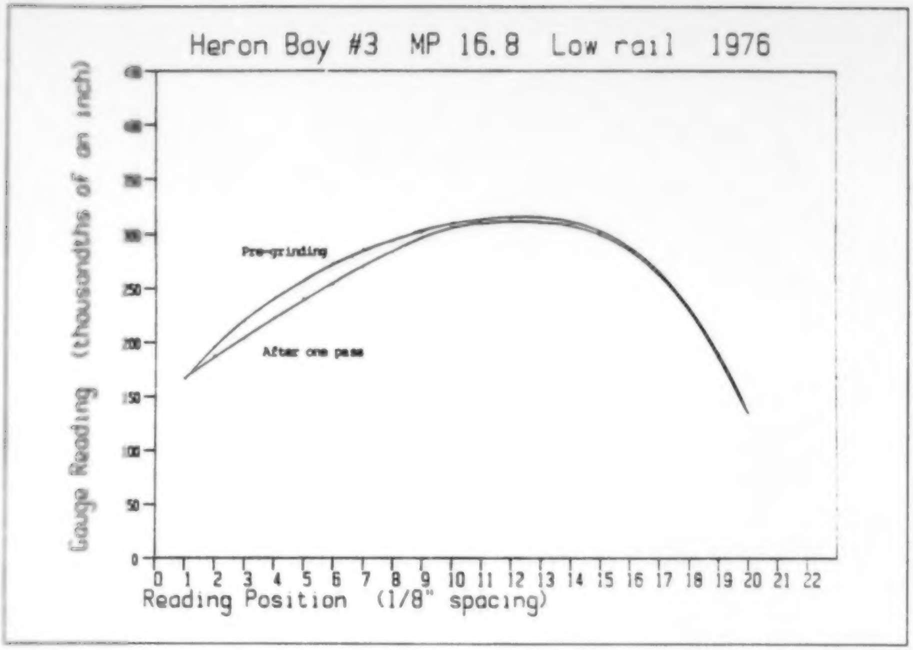


Figure C.3: Measured rail head profiles at test site 1.3 before and after grinding

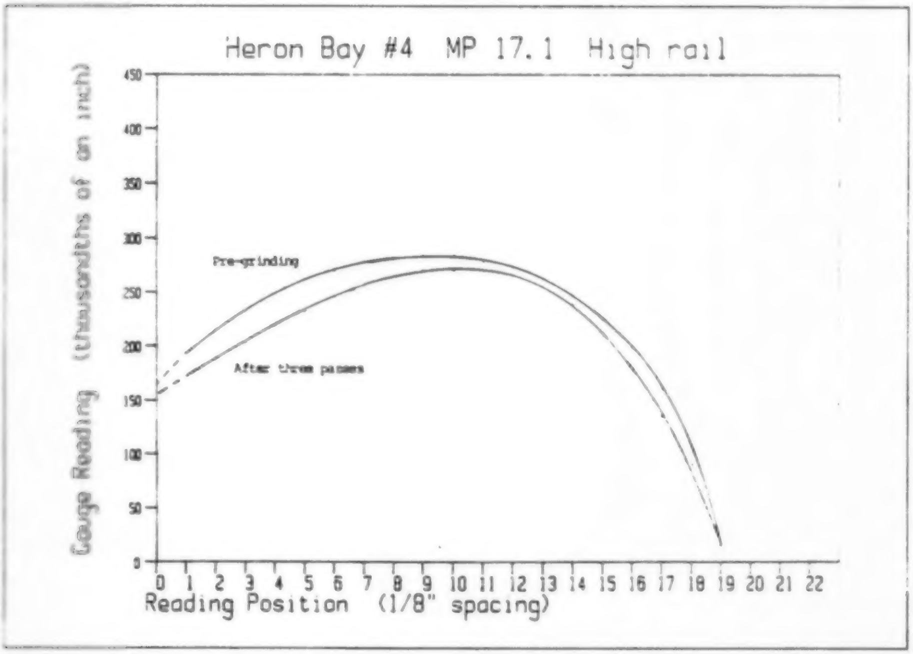


Figure C.4: Measured rail head profiles at test site 1.4 before and after grinding

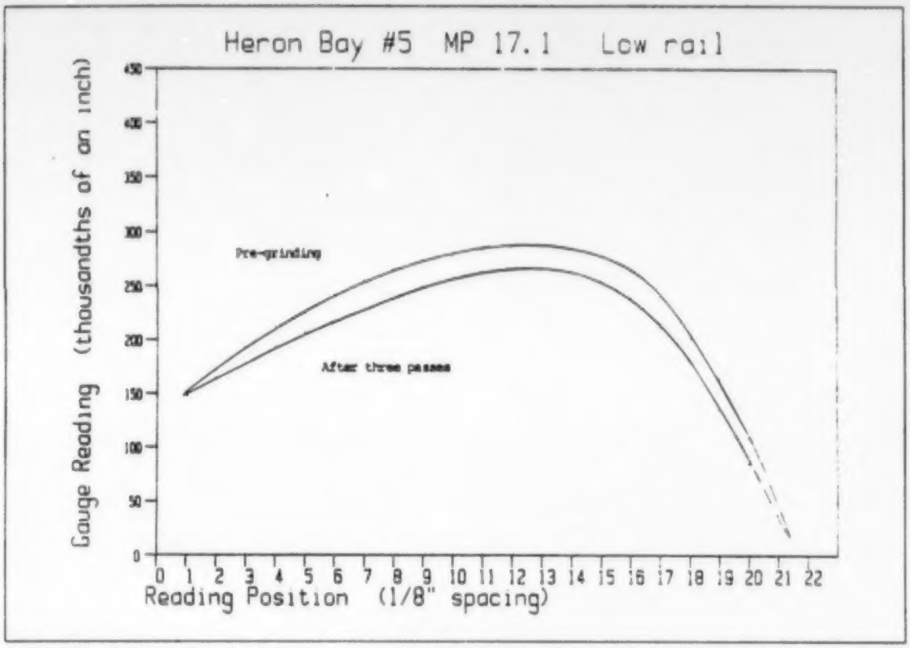


Figure C.5: Measured rail head profiles at test site 1.5 before and after grinding

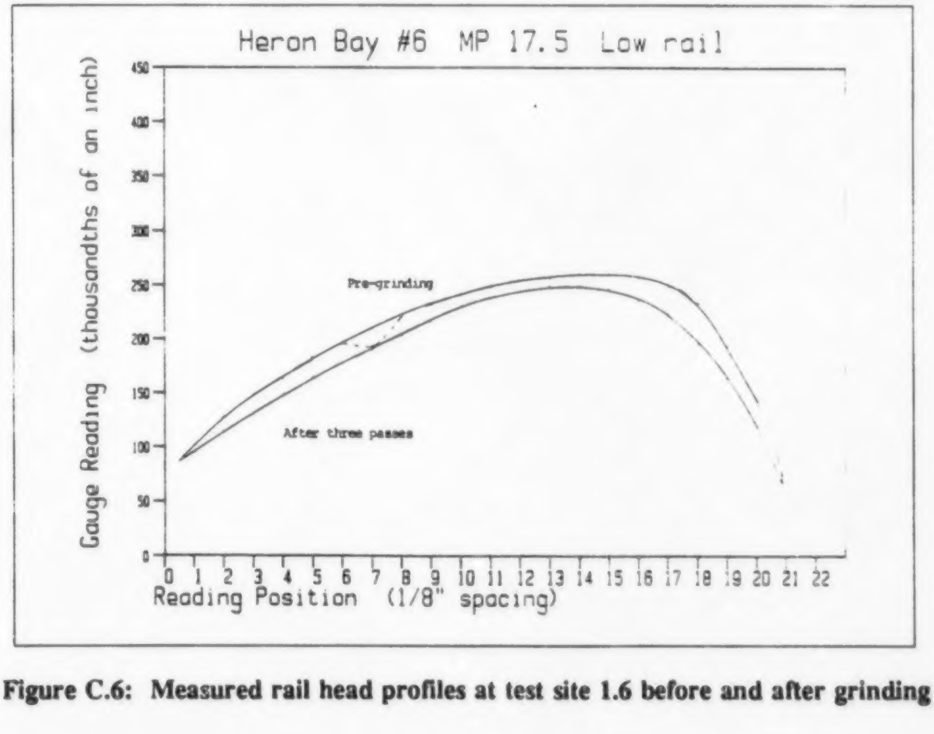


Figure C.6: Measured rail head profiles at test site 1.6 before and after grinding

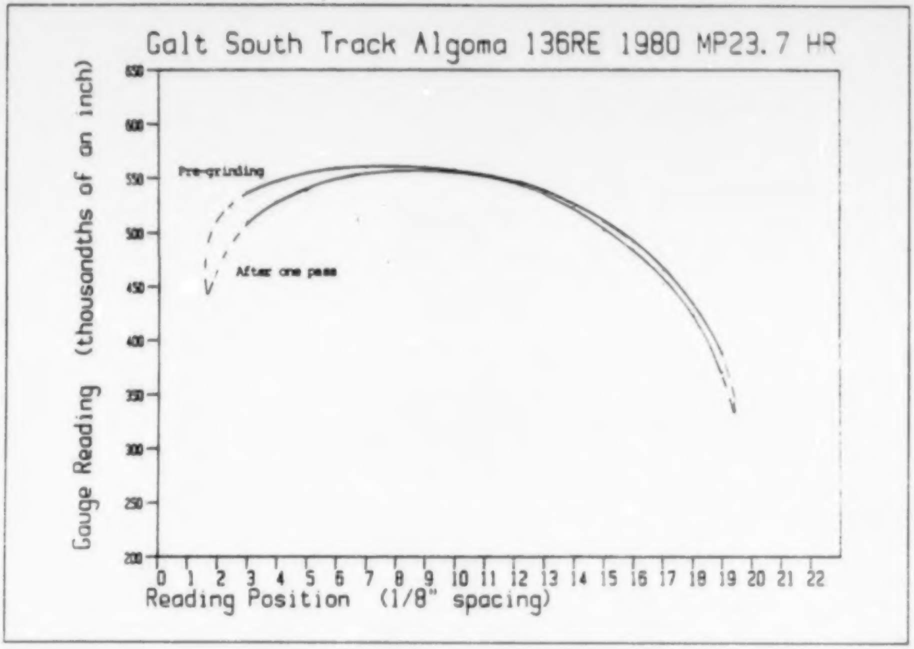


Figure C.7: Measured rail head profiles at test site 2.1 before and after grinding

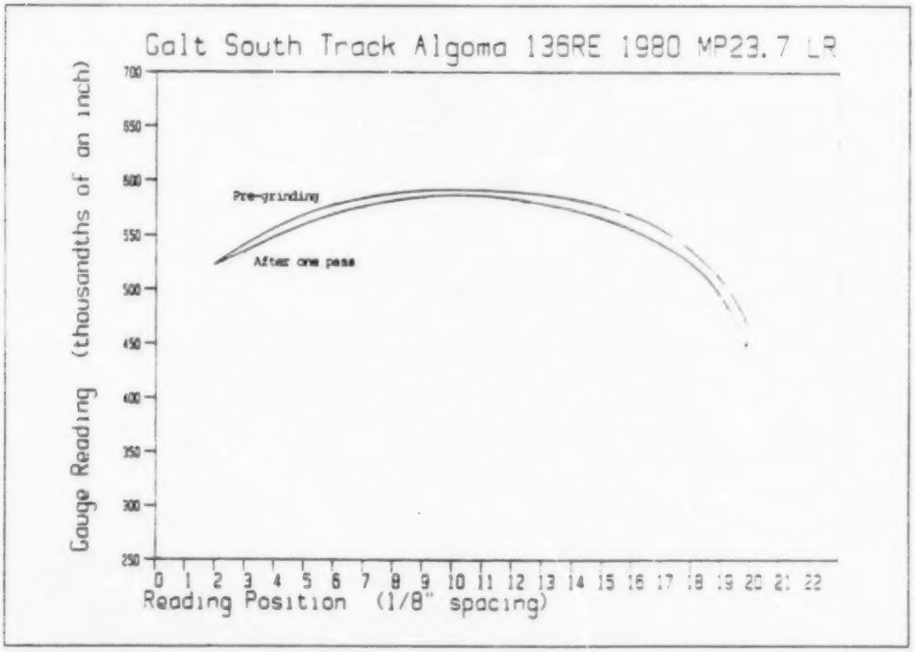


Figure C.8: Measured rail head profiles at test site 2.2 before and after grinding

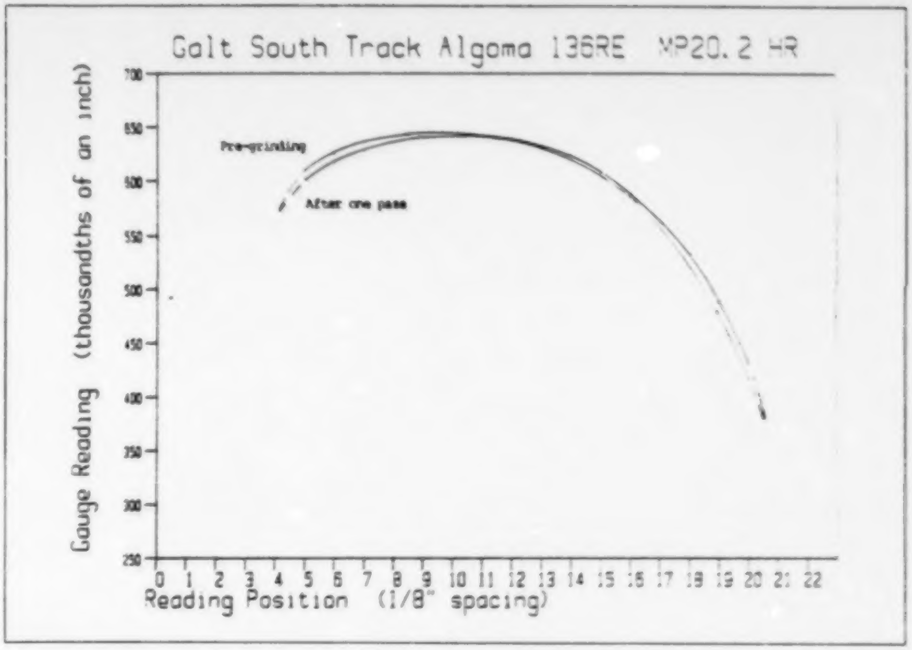


Figure C.9: Measured rail head profiles at test site 2.3 before and after grinding

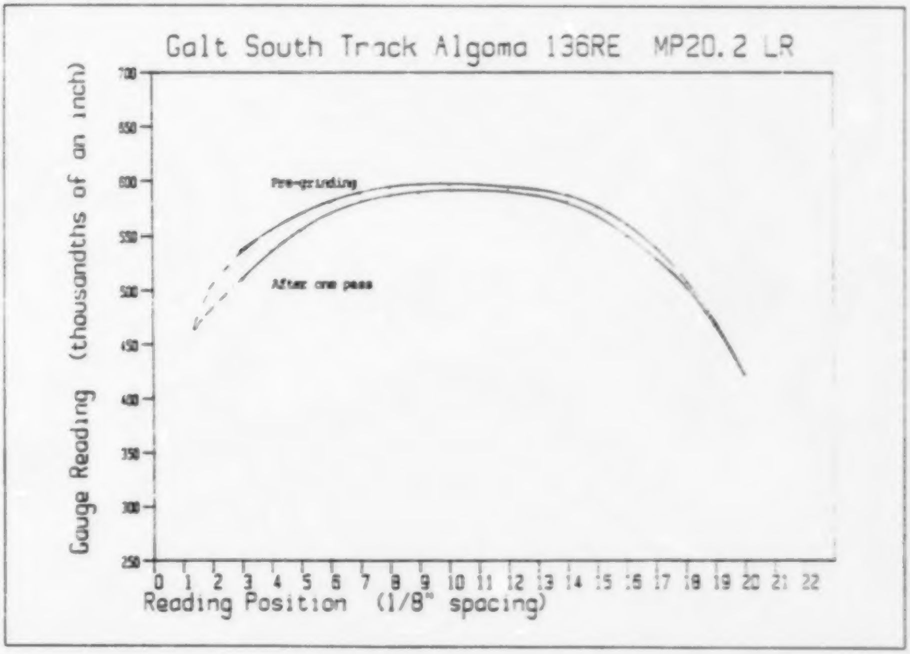


Figure C.10: Measured rail head profiles at test site 2.4 before and after grinding

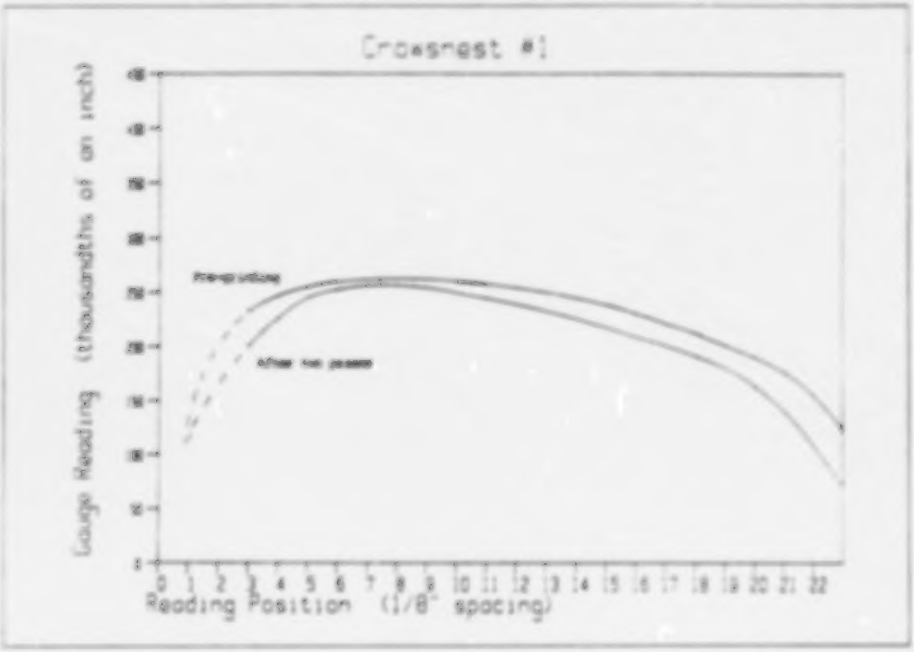


Figure C.11: Measured rail head profiles at test site 3.1 before and after grinding

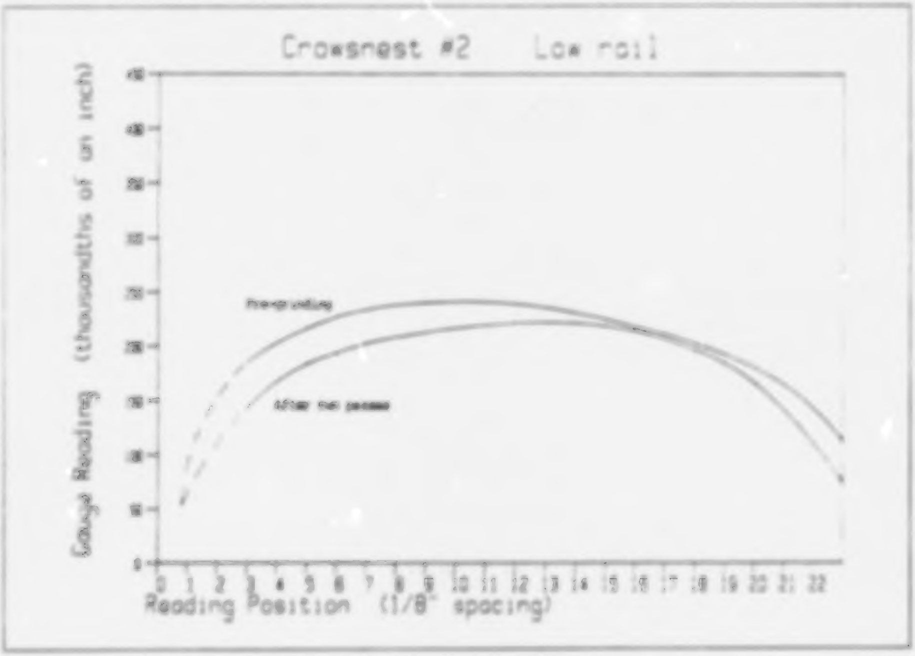


Figure C.12: Measured rail head profiles at test site 3.2 before and after grinding

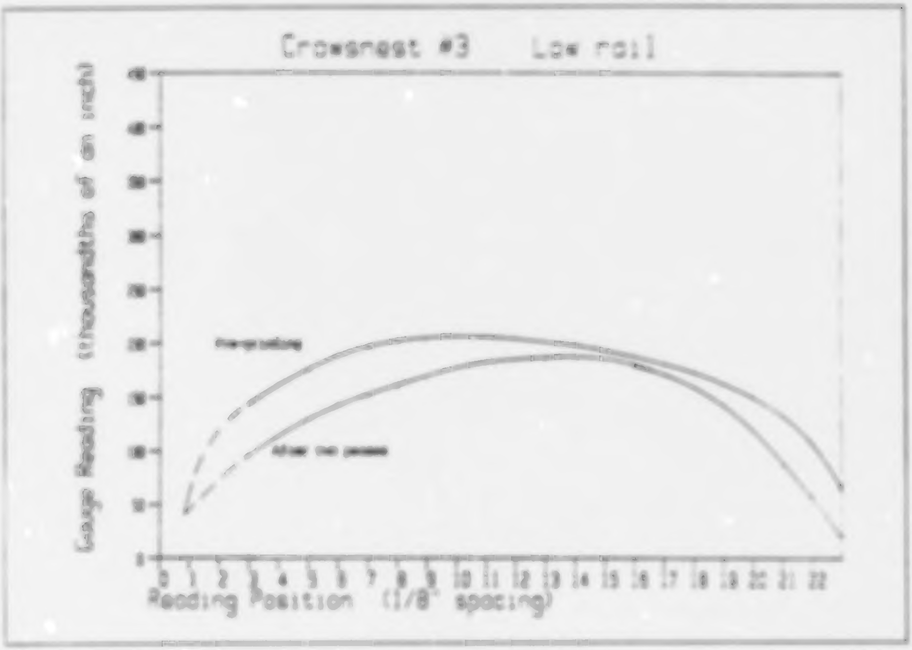


Figure C.13: Measured rail head profiles at test site 3.3 before and after grinding

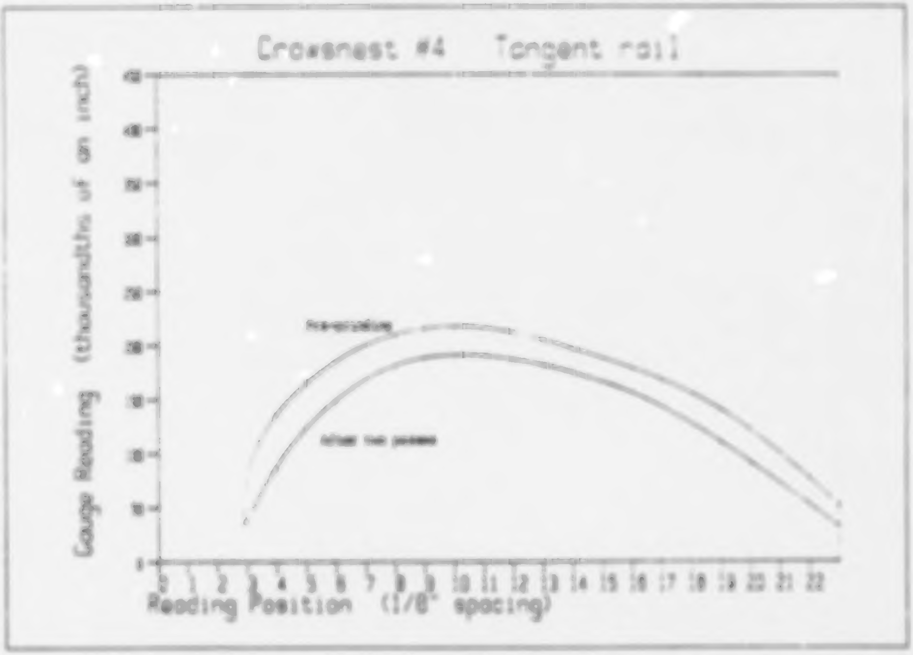


Figure C.14: Measured rail head profiles at test site 3.4 before and after grinding

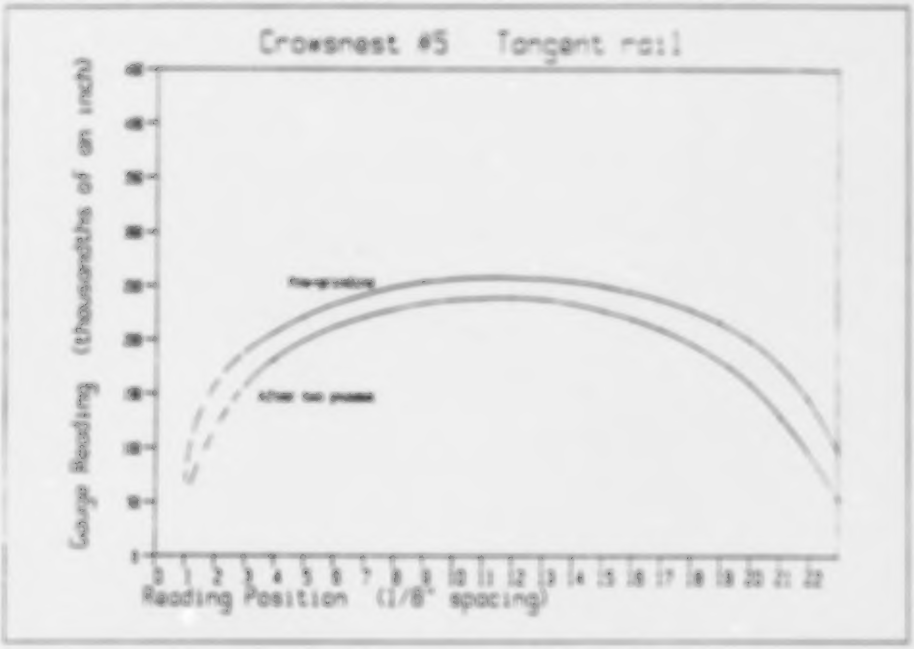


Figure C.15: Measured rail head profiles at test site 3.5 before and after grinding

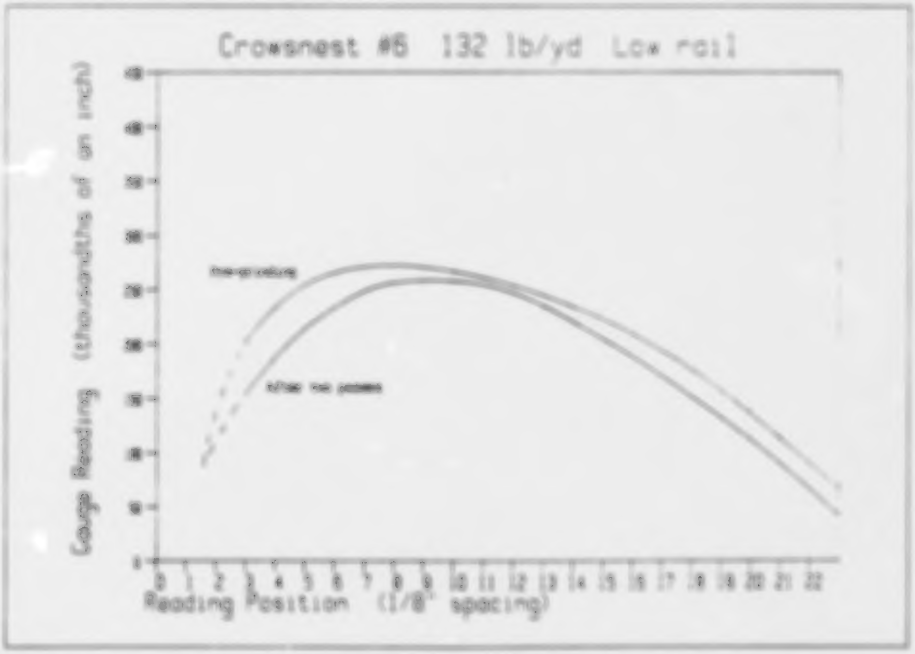


Figure C.16: Measured rail head profiles at test site 3.6 before and after grinding

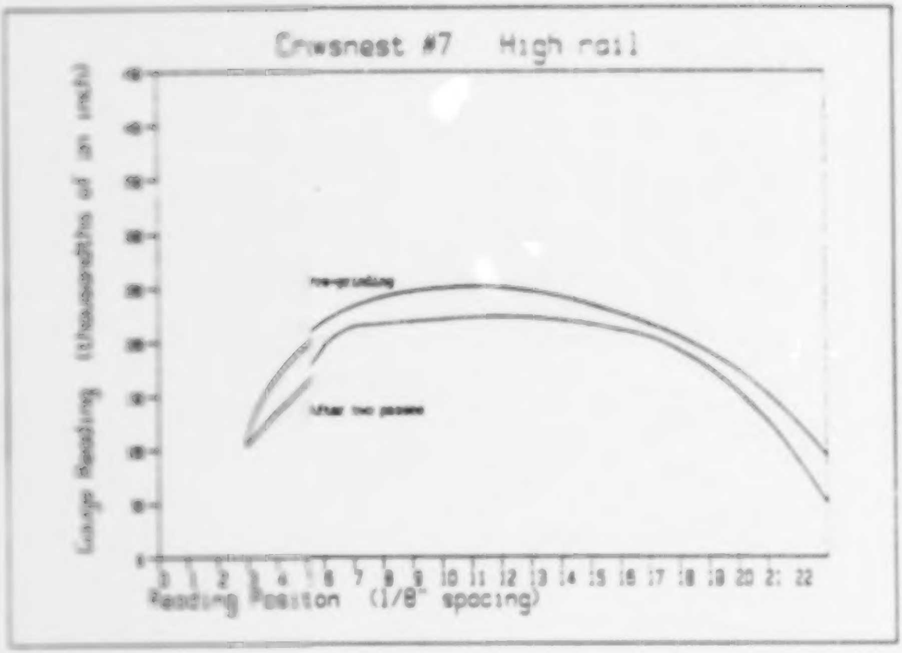


Figure C.17: Measured railhead profiles at test site 3.7 before and after grinding

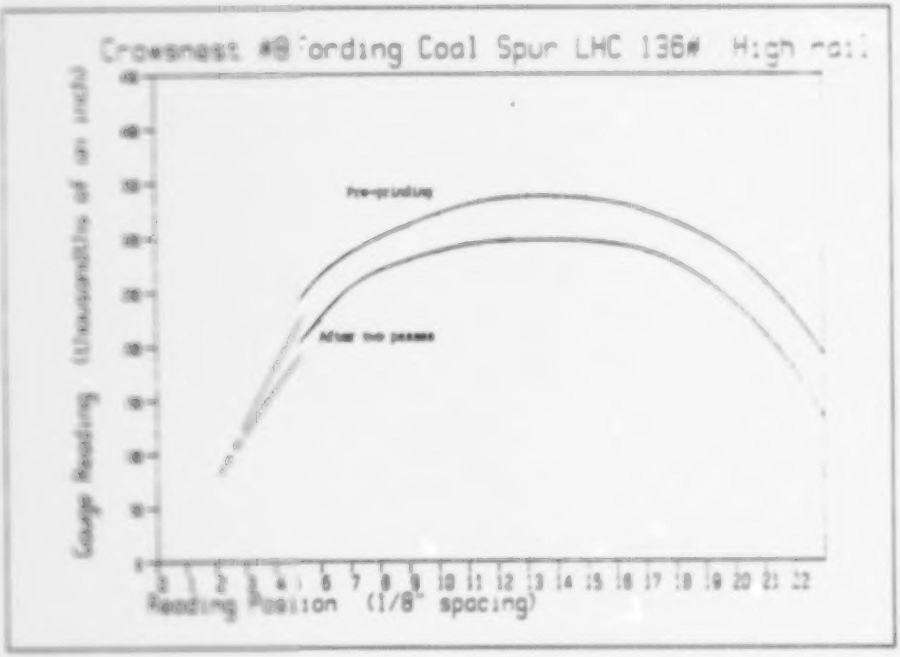


Figure C.18: Measured railhead profiles at test site 3.8 before and after grinding

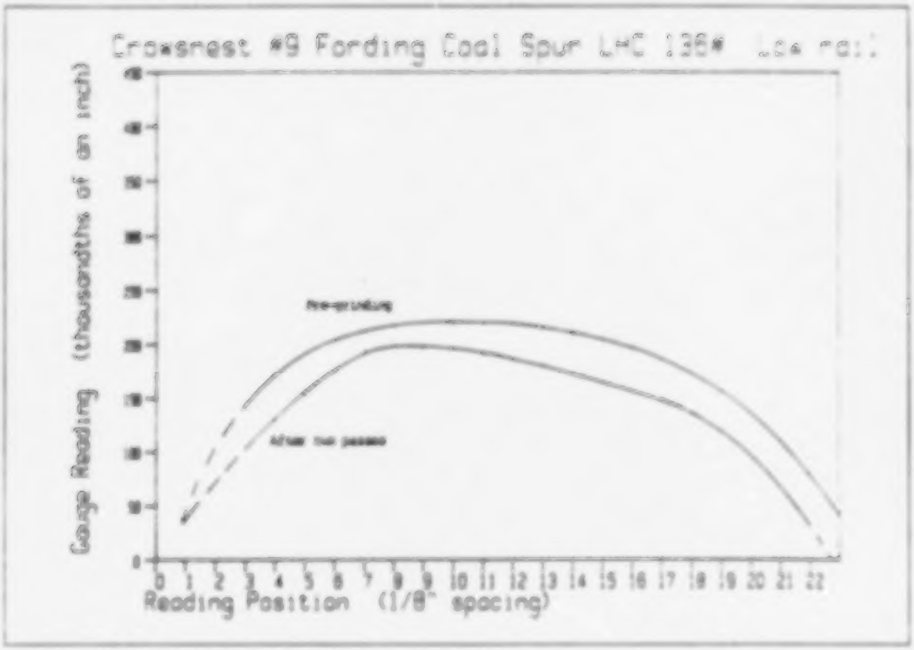


Figure C.19: Measured rail head profiles at test site 3.9 before and after grinding

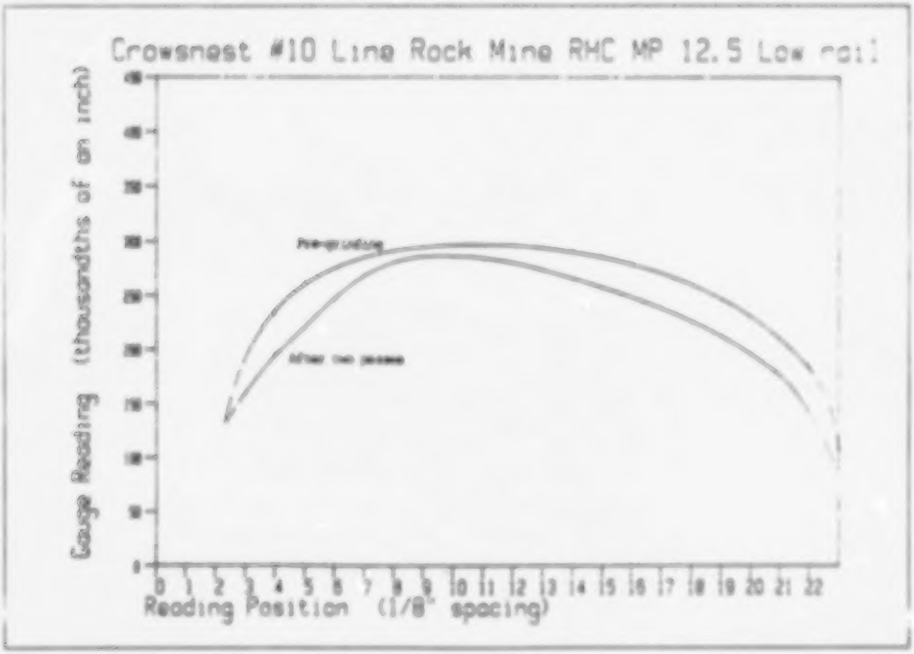


Figure C.20: Measured rail head profiles at test site 3.10 before and after grinding

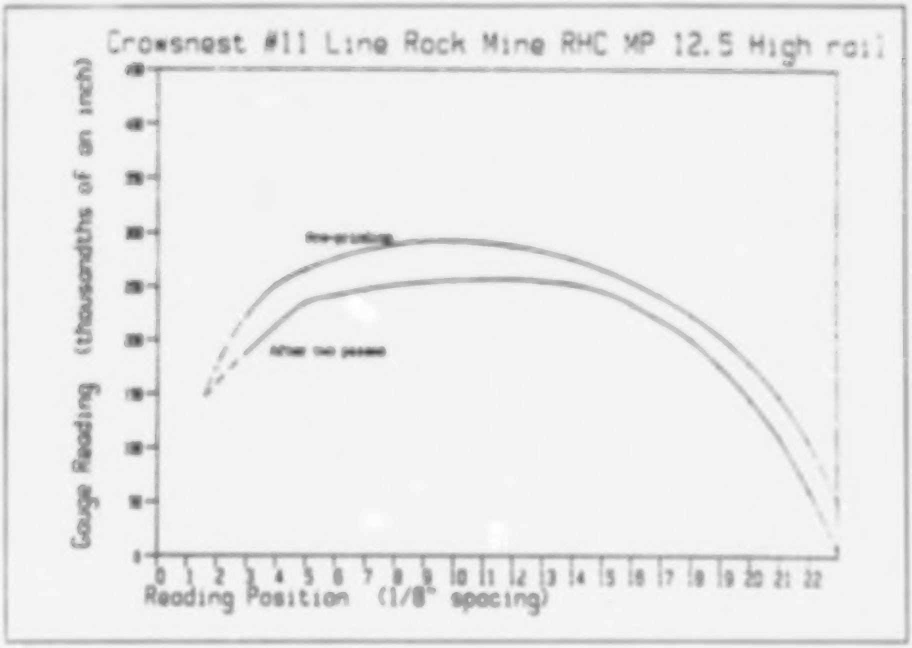


Figure C.21: Measured rail head profiles at test site 3.11 before and after grinding

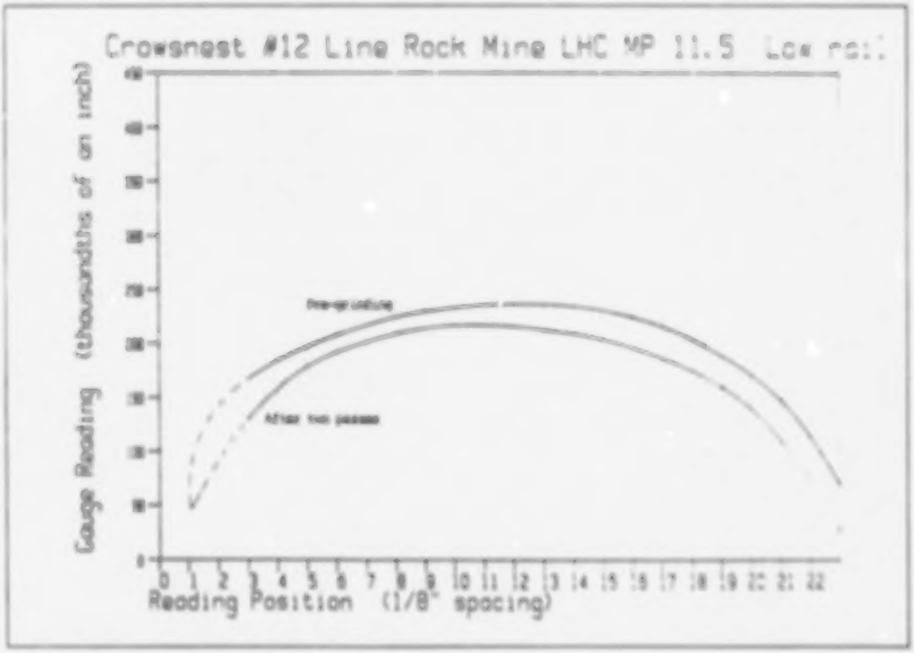


Figure C.22: Measured rail head profiles at test site 3.12 before and after grinding

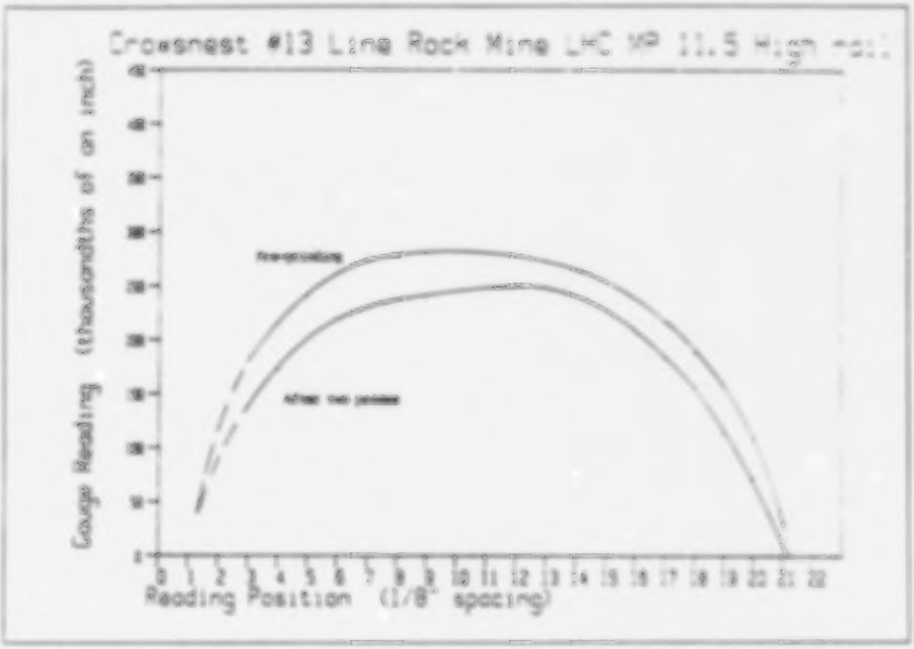


Figure C.23: Measured rail head profiles at test site 3.13 before and after grinding

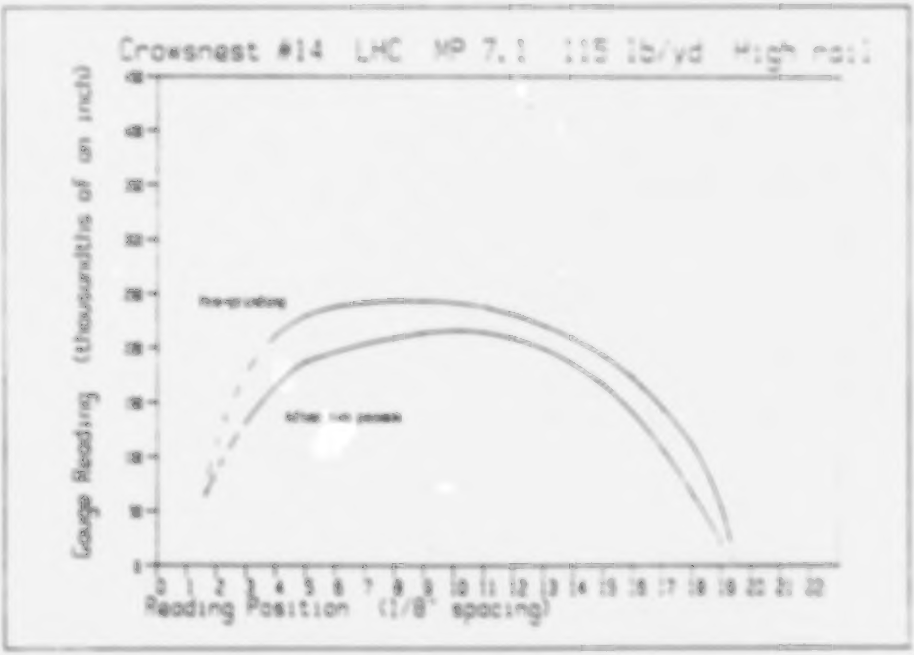


Figure C.24: Measured rail head profiles at test site 3.14 before and after grinding

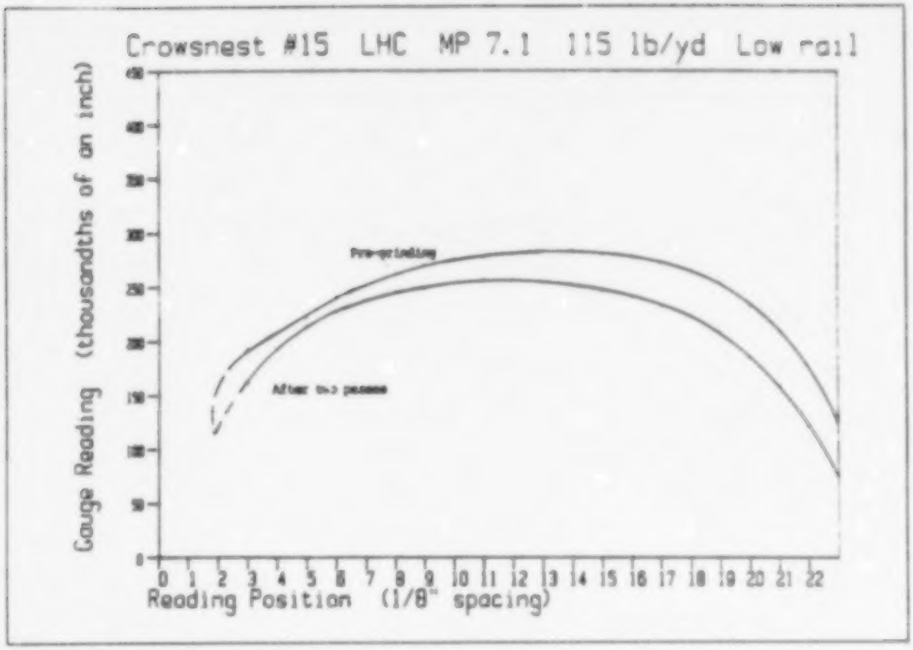


Figure C.25: Measured rail head profiles at test site 3.15 before and after grinding

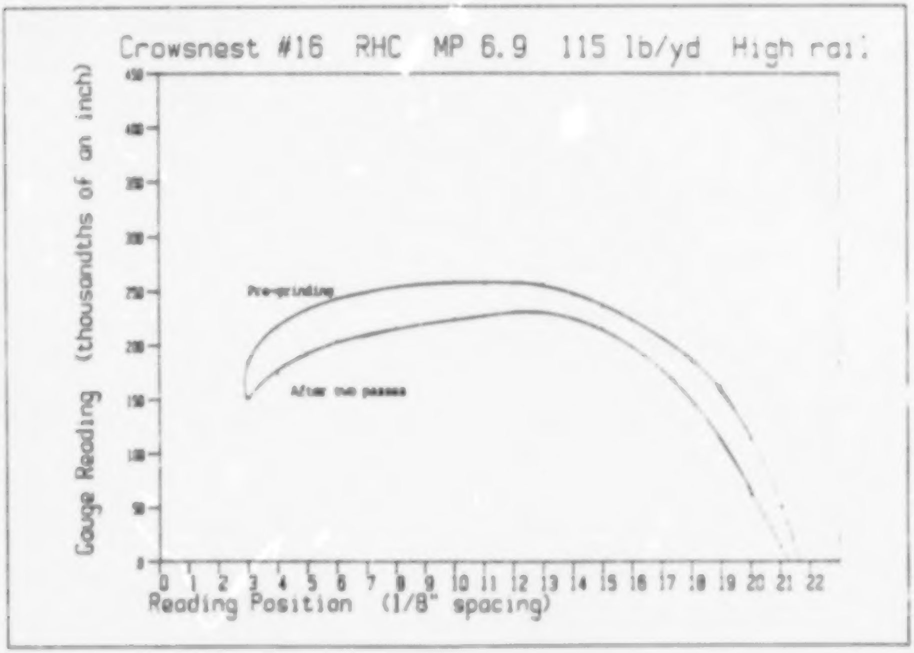


Figure C.26: Measured rail head profiles at test site 3.16 before and after grinding

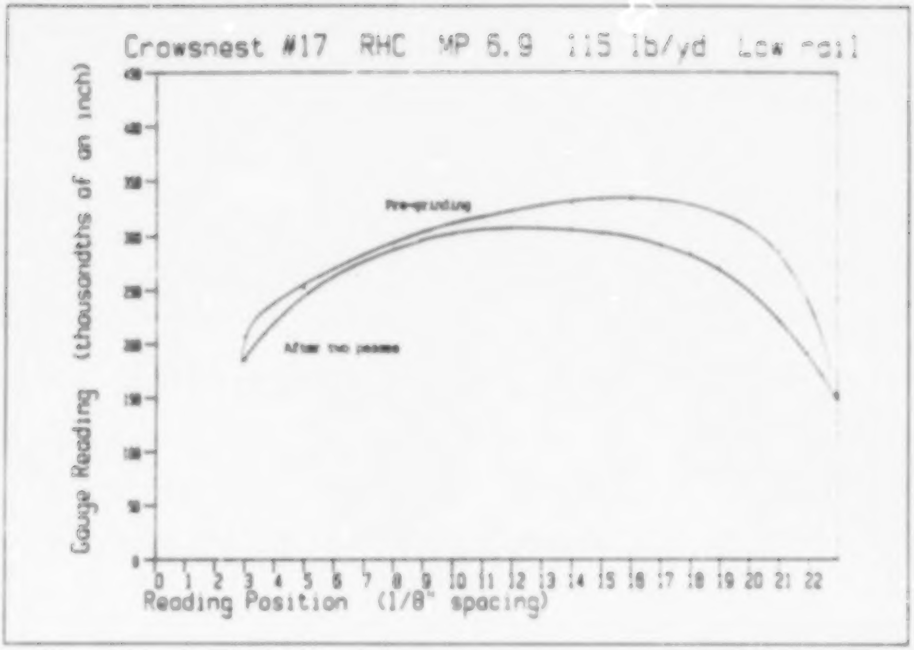


Figure C.27: Measured rail head profiles at test site 3.17 before and after grinding

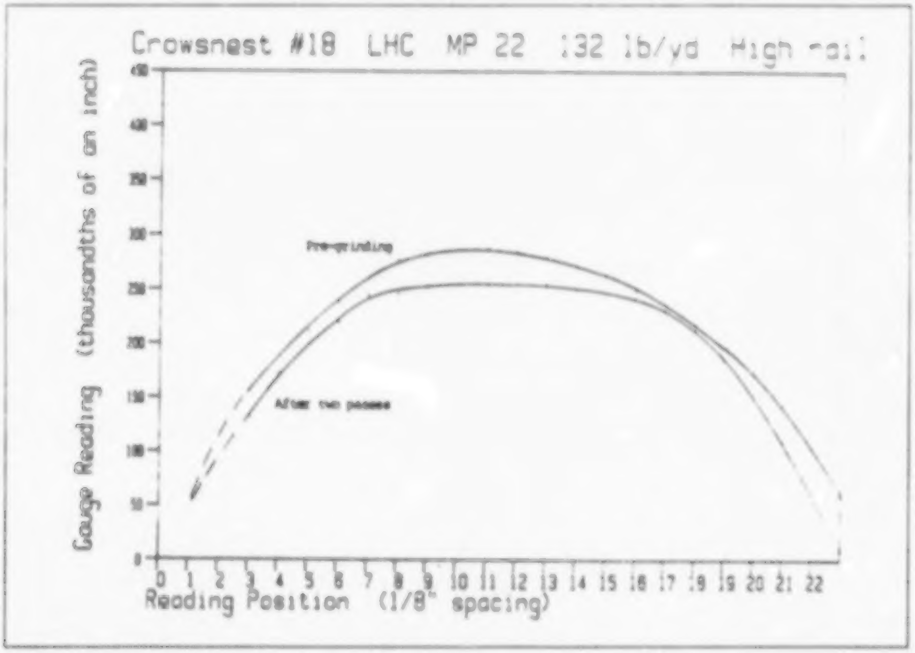


Figure C.28: Measured rail head profiles at test site 3.18 before and after grinding

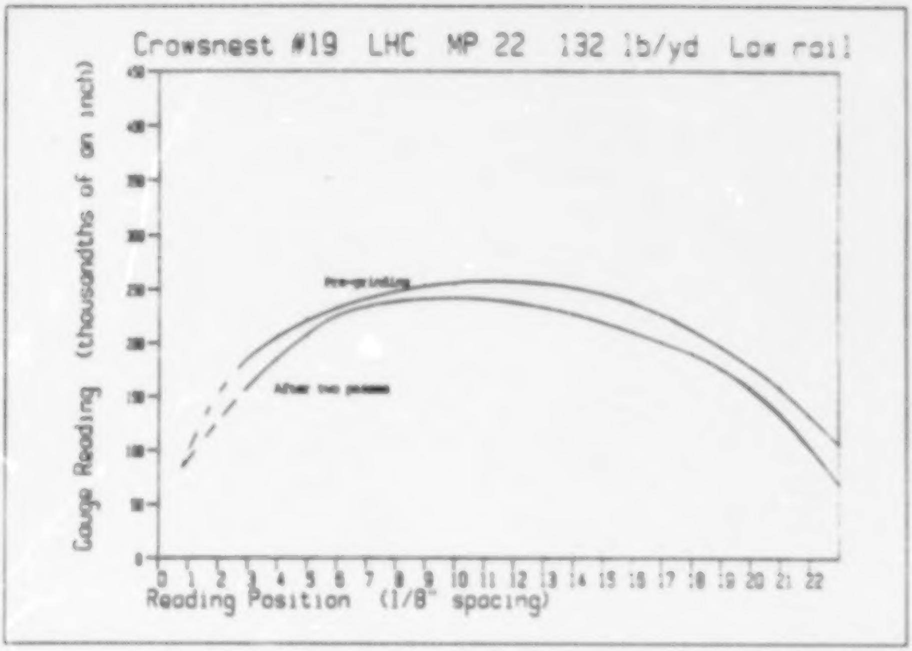


Figure C.29: Measured rail head profiles at test site 3.19 before and after grinding

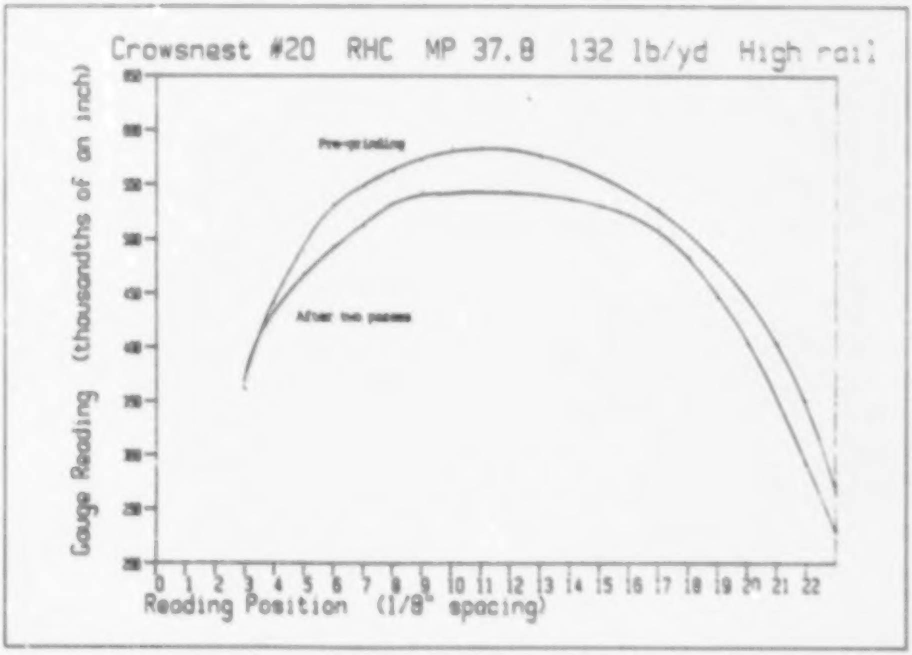


Figure C.30: Measured rail head profiles at test site 3.20 before and after grinding

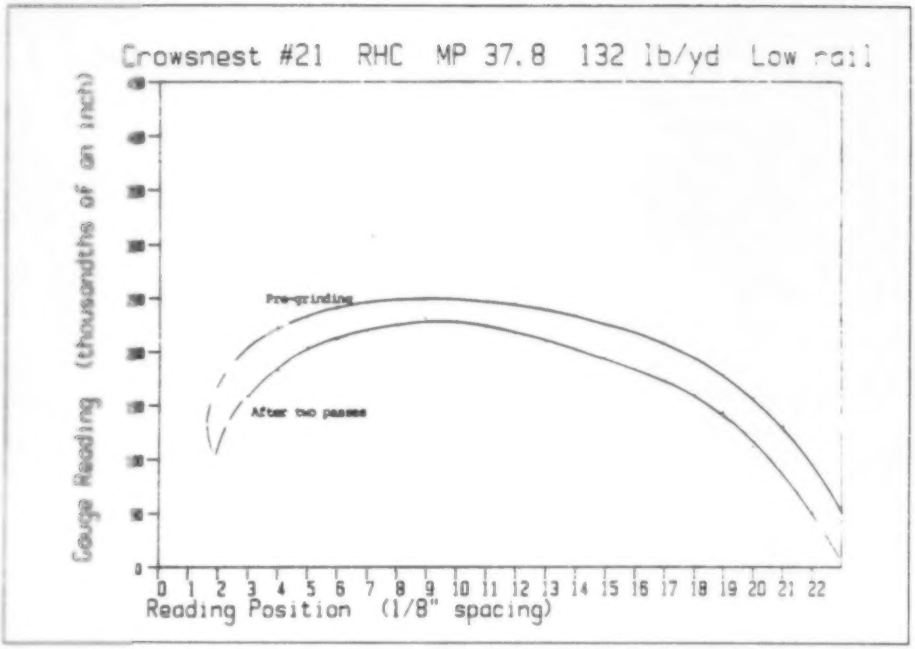


Figure C.31: Measured rail head profiles at test site 3.21 before and after grinding

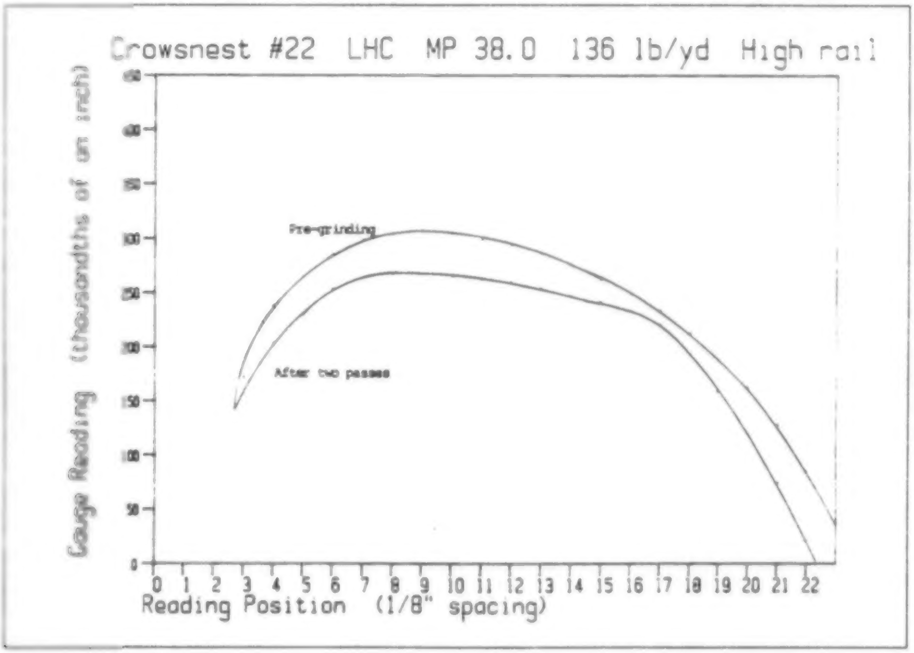


Figure C.32: Measured rail head profiles at test site 3.22 before and after grinding

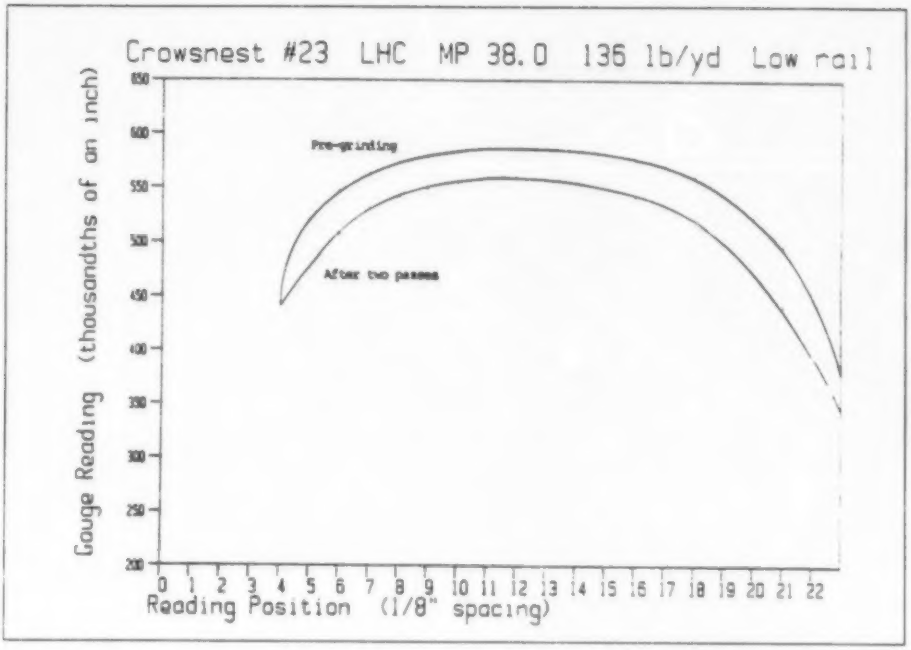


Figure C.33: Measured rail head profiles at test site 3.23 before and after grinding

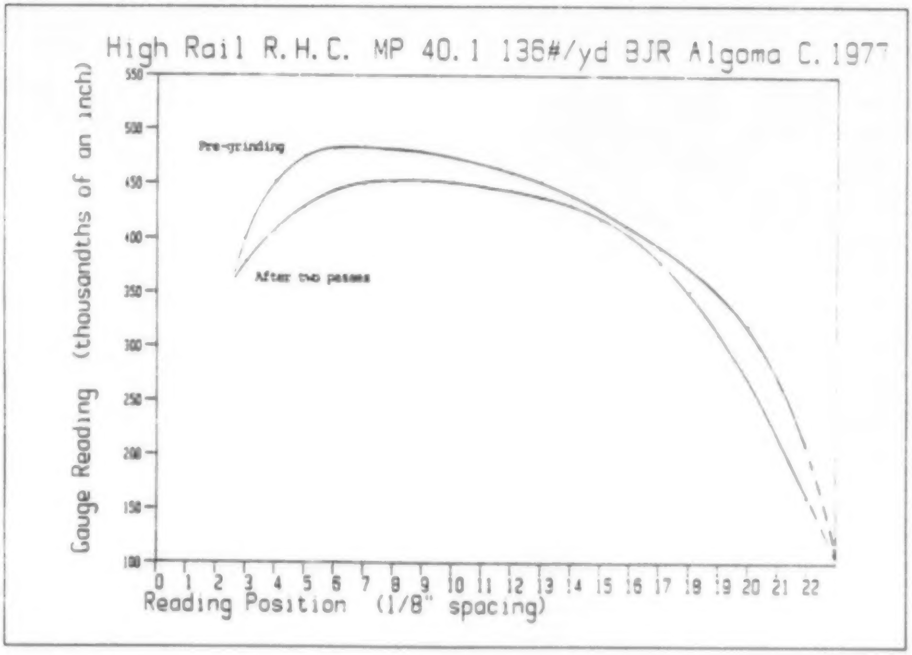


Figure C.34: Measured rail head profiles at test site 4.1 before and after grinding

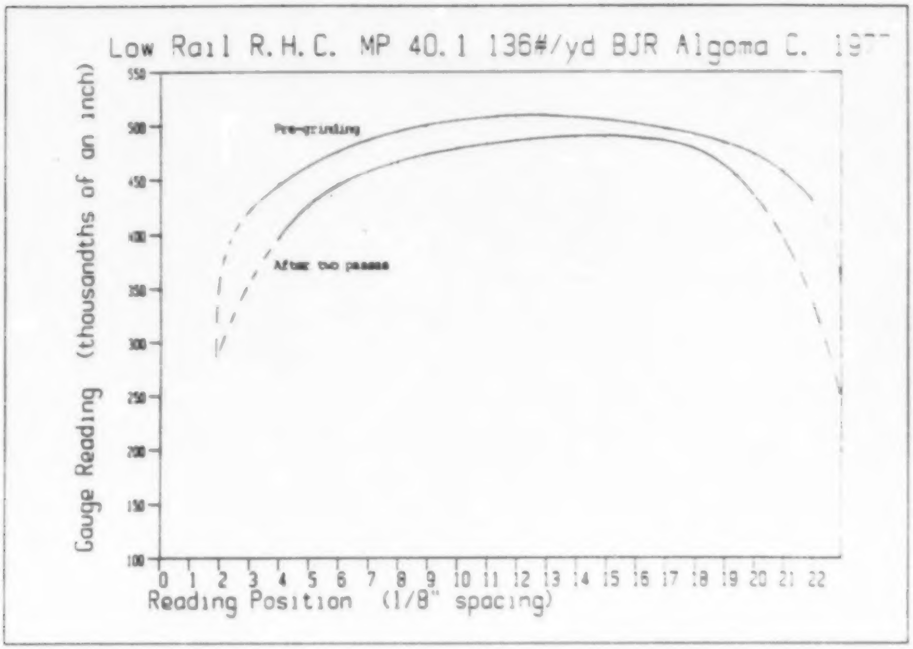


Figure C.35: Measured rail head profiles at test site 4.2 before and after grinding

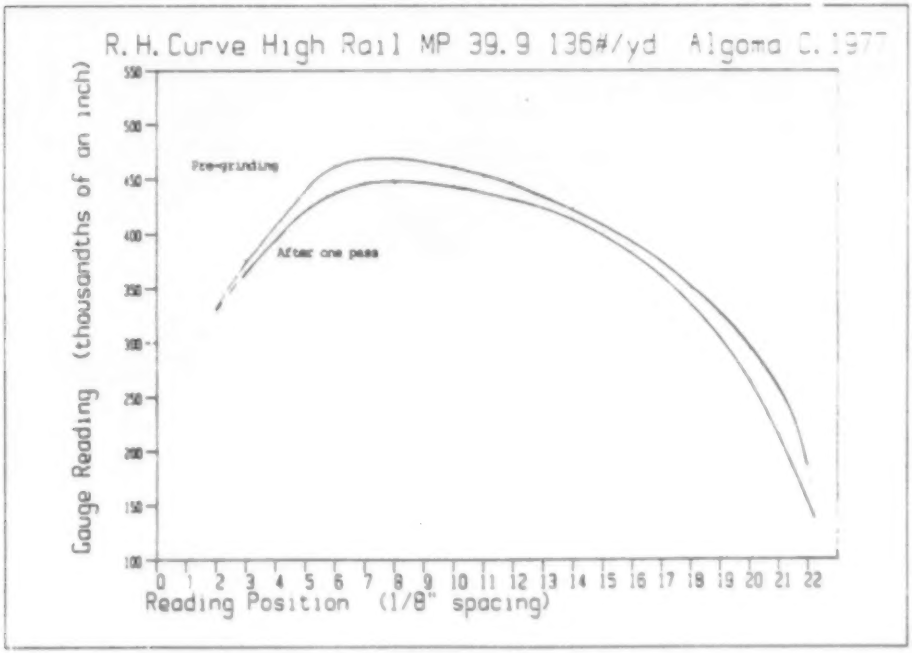


Figure C.36: Measured rail head profiles at test site 4.3 before and after grinding

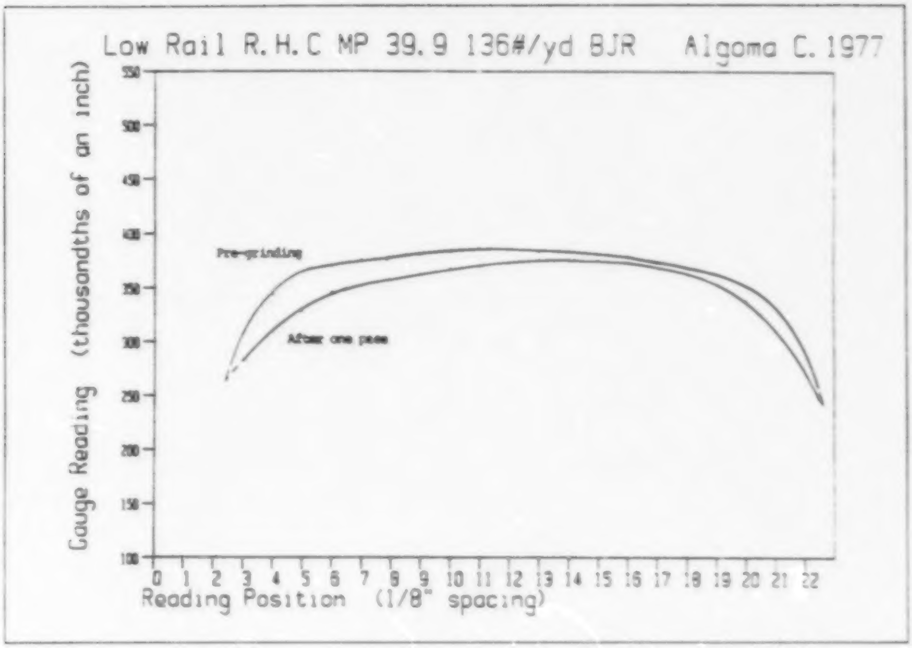


Figure C.37: Measured rail head profiles at test site 4.4 before and after grinding

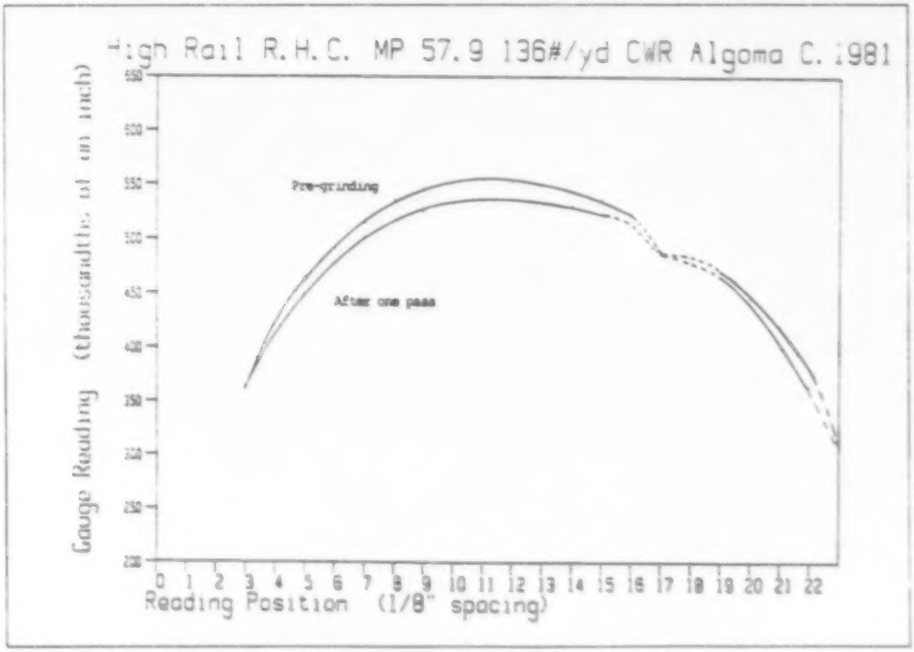


Figure C.38: Measured rail head profiles at test site 4.5 before and after grinding

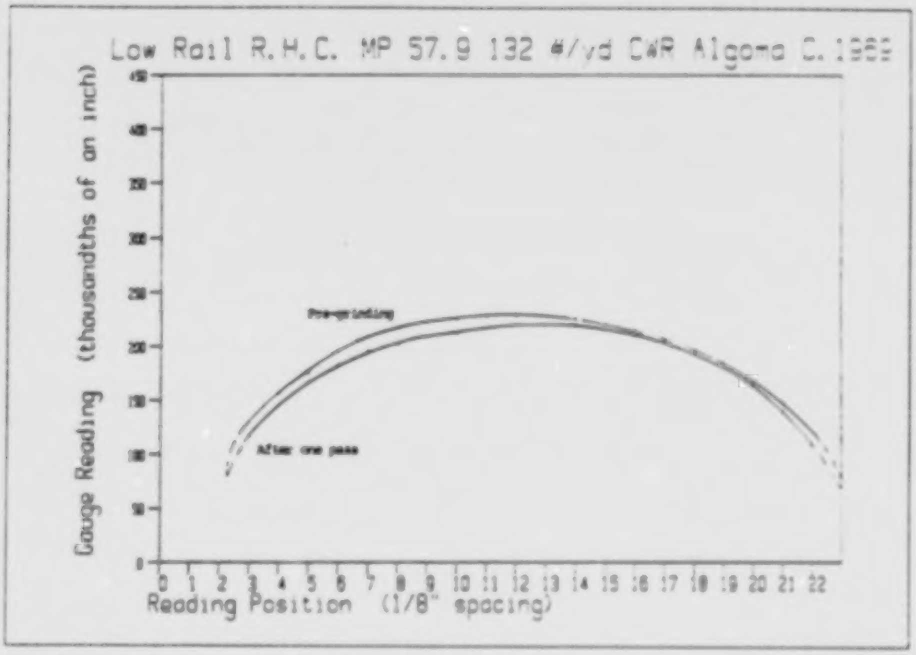


Figure C.39: Measured rail head profiles at test site 4.6 before and after grinding

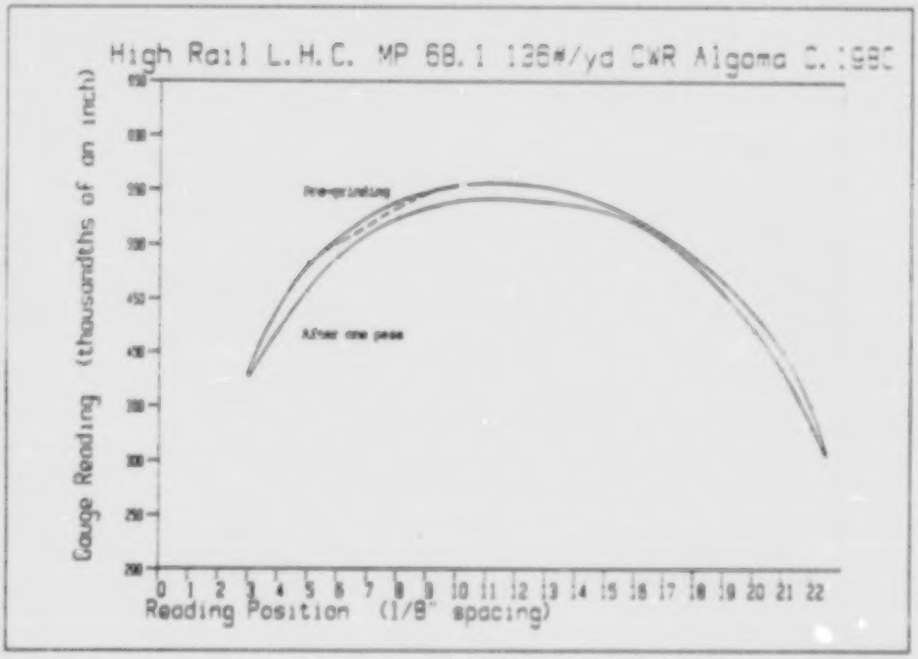


Figure C.40: Measured rail head profiles at test site 4.7 before and after grinding

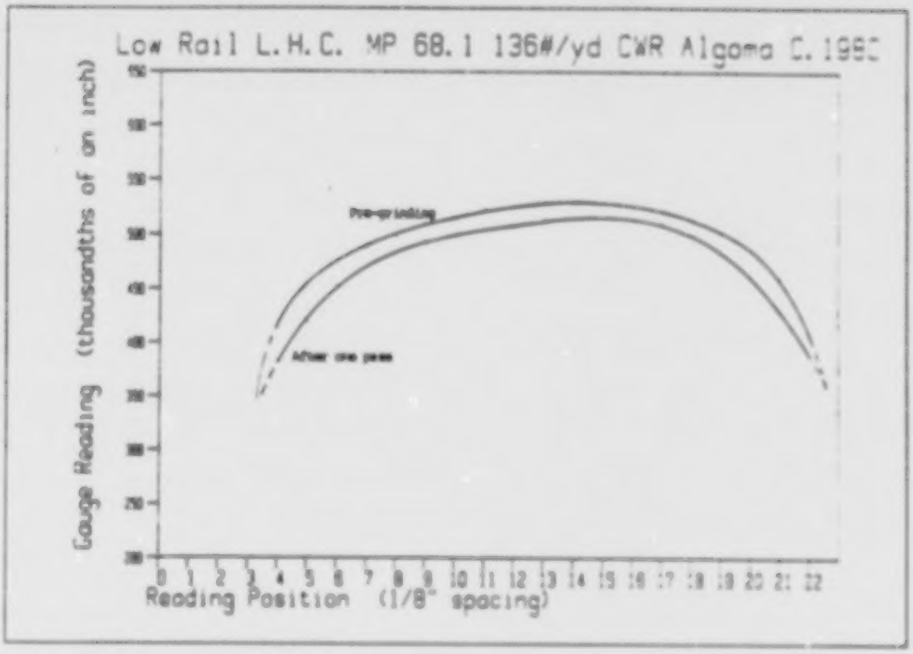


Figure C.41: Measured rail head profiles at test site 4.8 before and after grinding

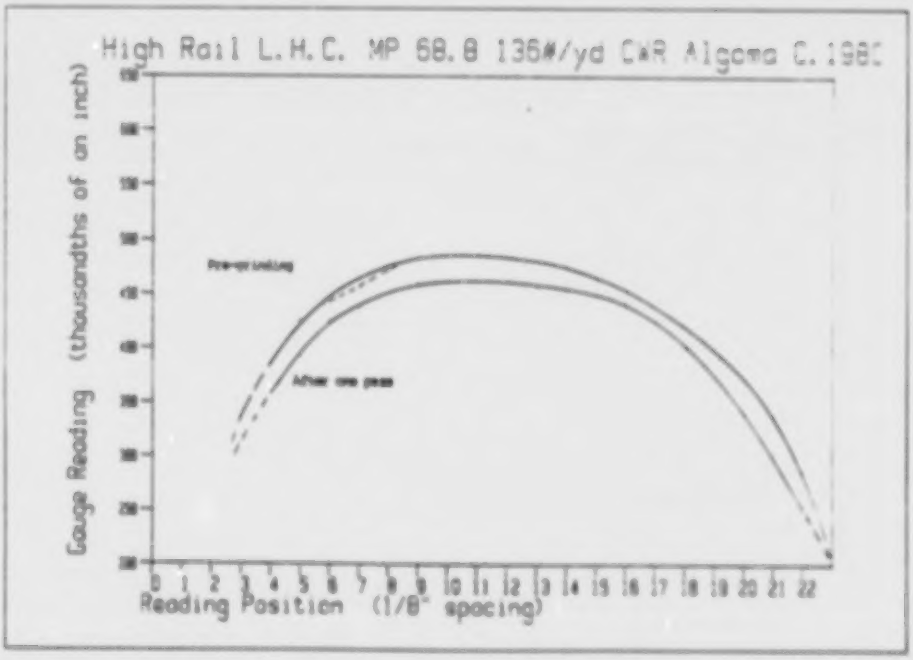


Figure C.42: Measured rail head profiles at test site 4.9 before and after grinding

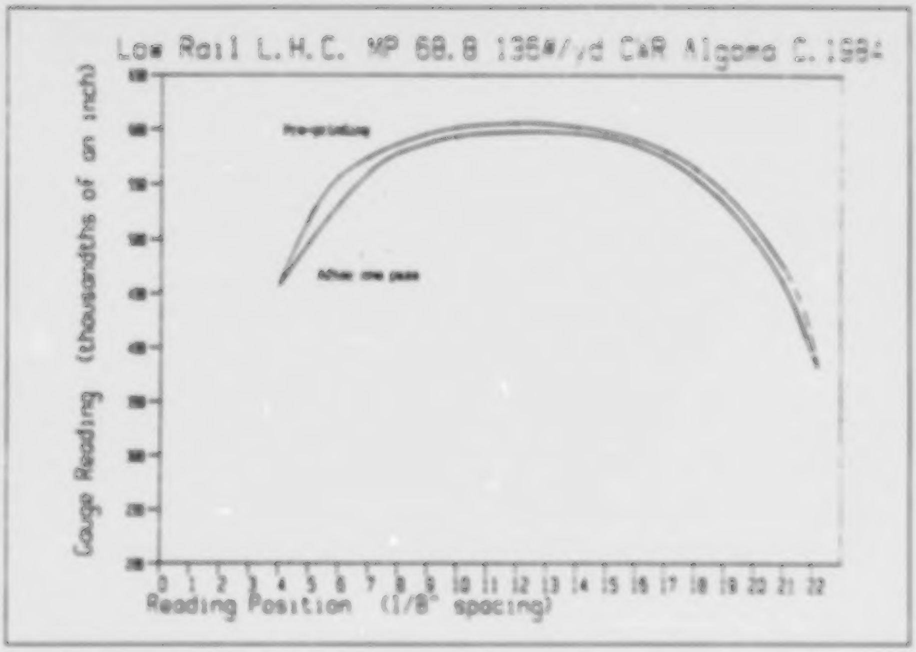


Figure C.43: Measured rail head profiles at test site 4.10 before and after grinding

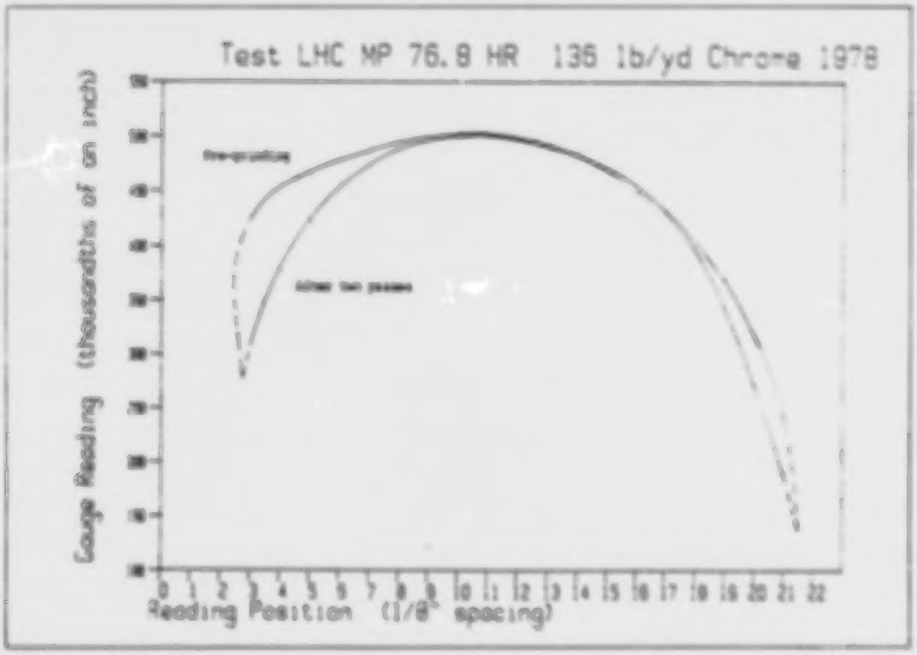


Figure C.44: Measured rail head profiles at test site 5.1 before and after grinding

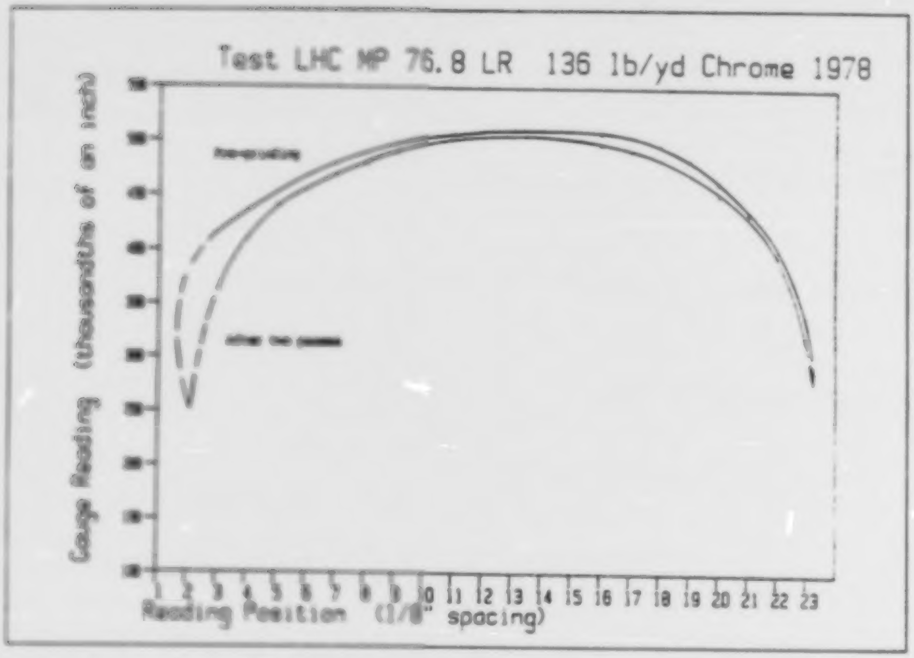


Figure C.45: Measured rail head profiles at test site 5.2 before and after grinding

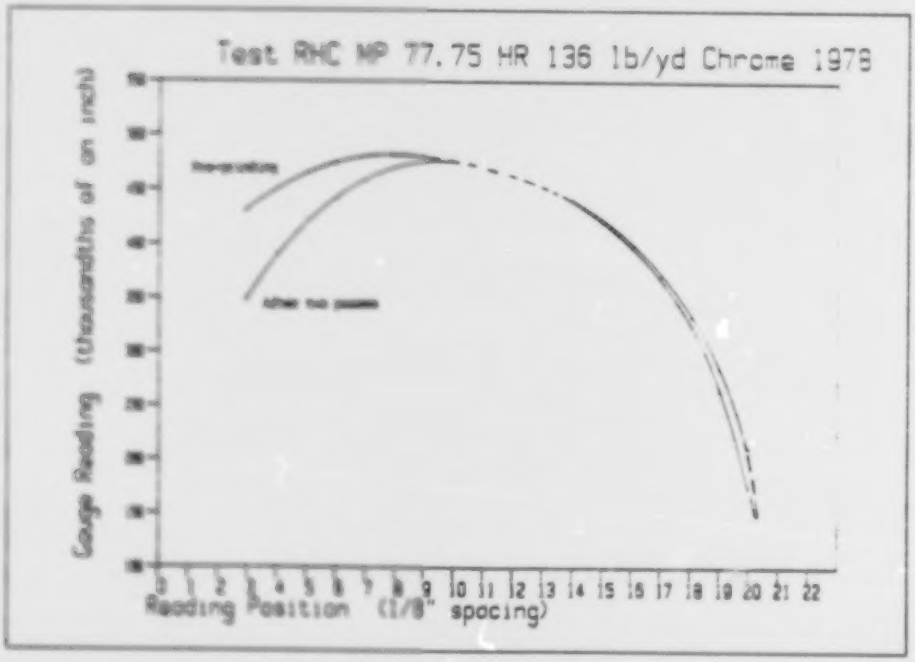


Figure C.46: Measured rail head profiles at test site 5.3 before and after grinding

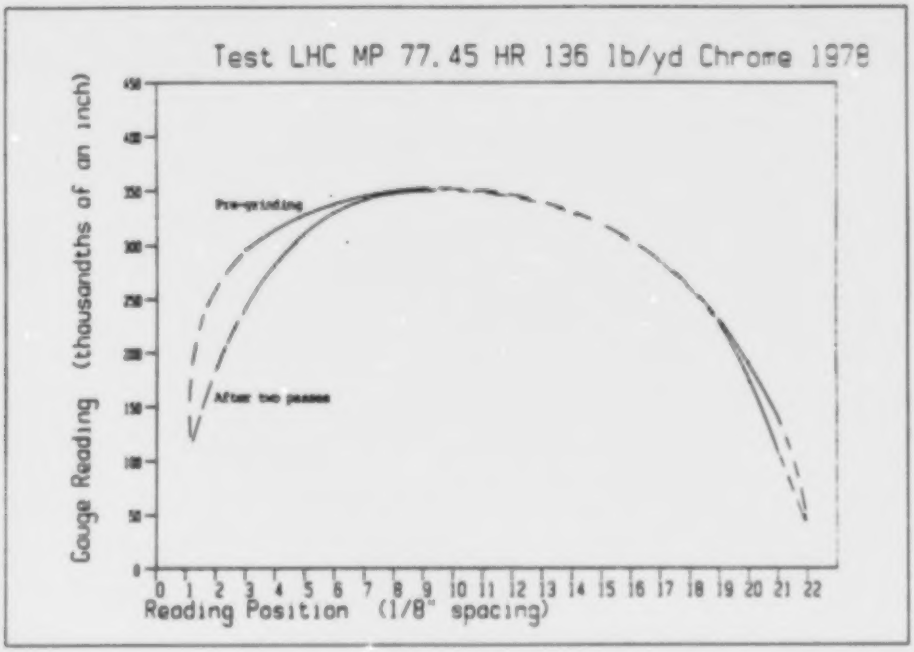


Figure C.47: Measured rail head profiles at test site 5.4 before and after grinding

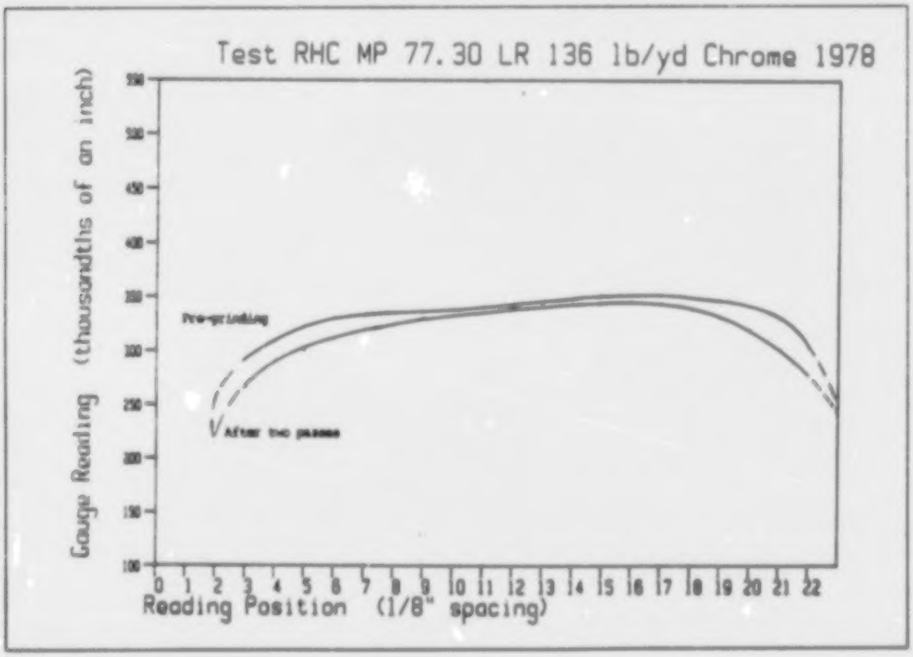


Figure C.48: Measured rail head profiles at test site 5.5 before and after grinding

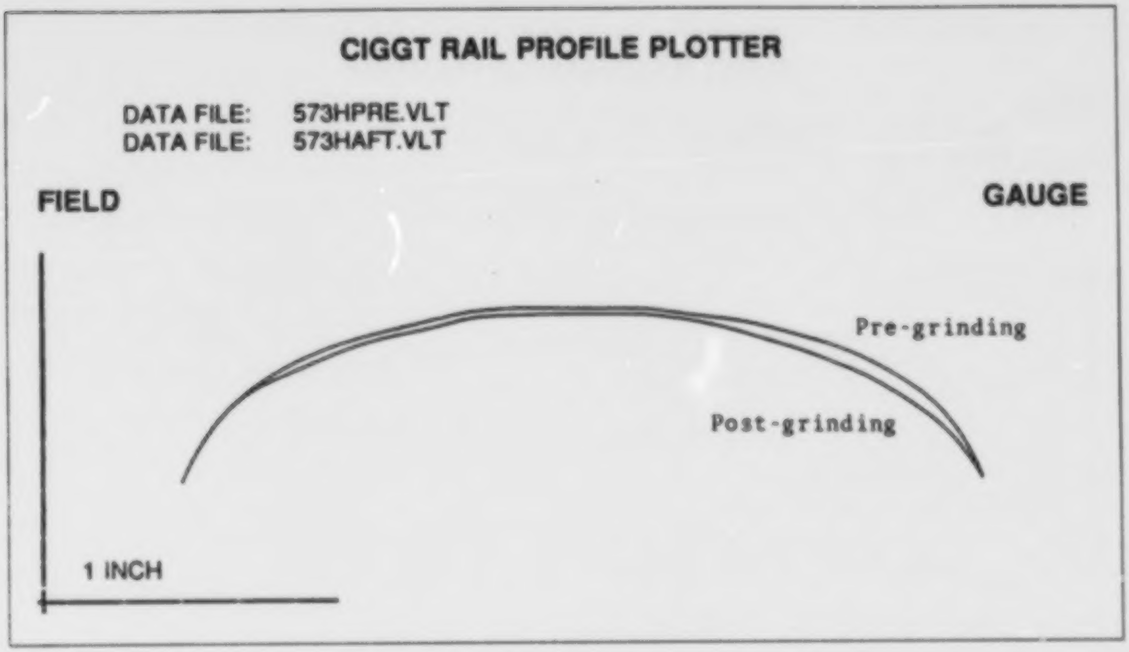


Figure C.49: Measured railhead profiles at test site 6.1 before and after grinding

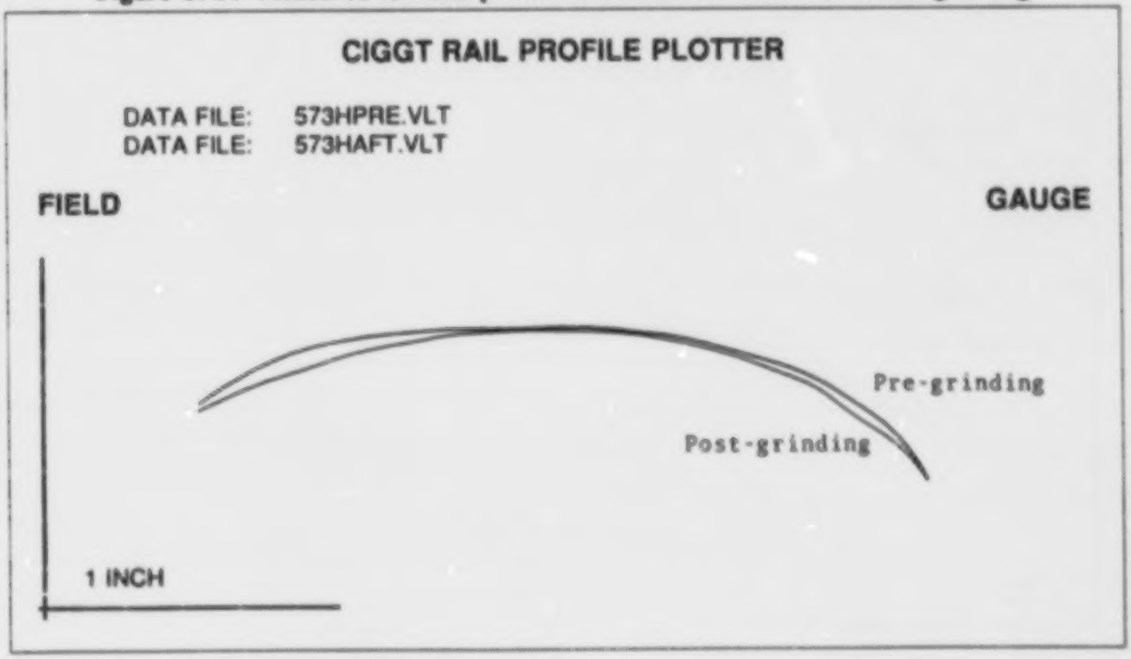


Figure C.50: Measured railhead profiles at test site 6.2 before and after grinding

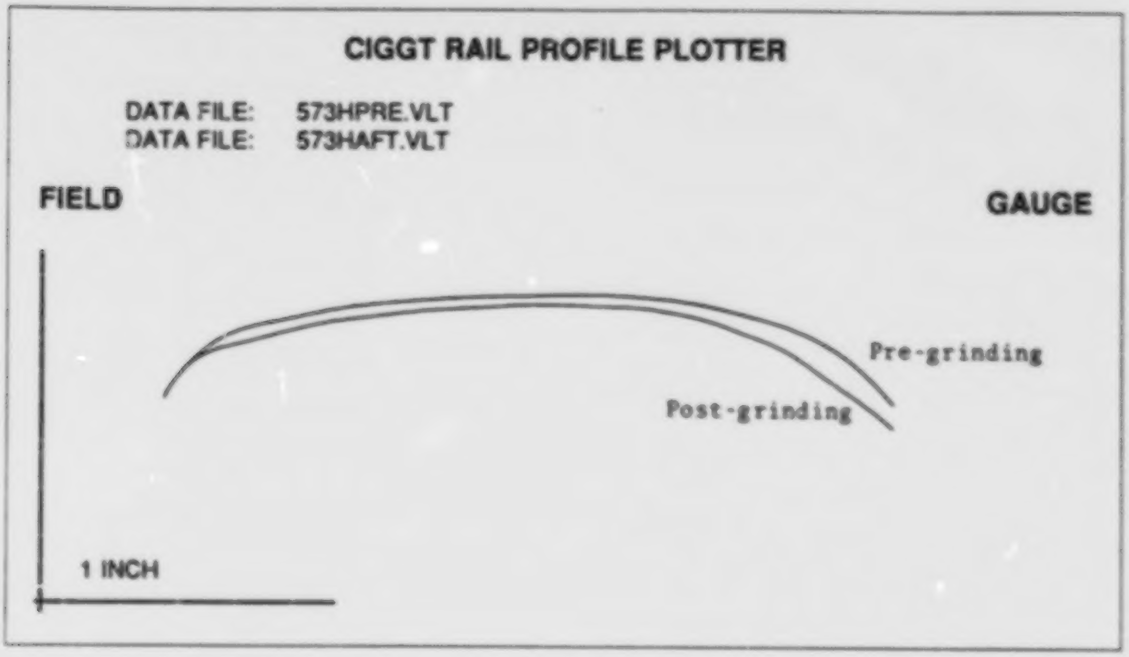


Figure C.51: Measured railhead profiles at test site 7.1 before and after grinding

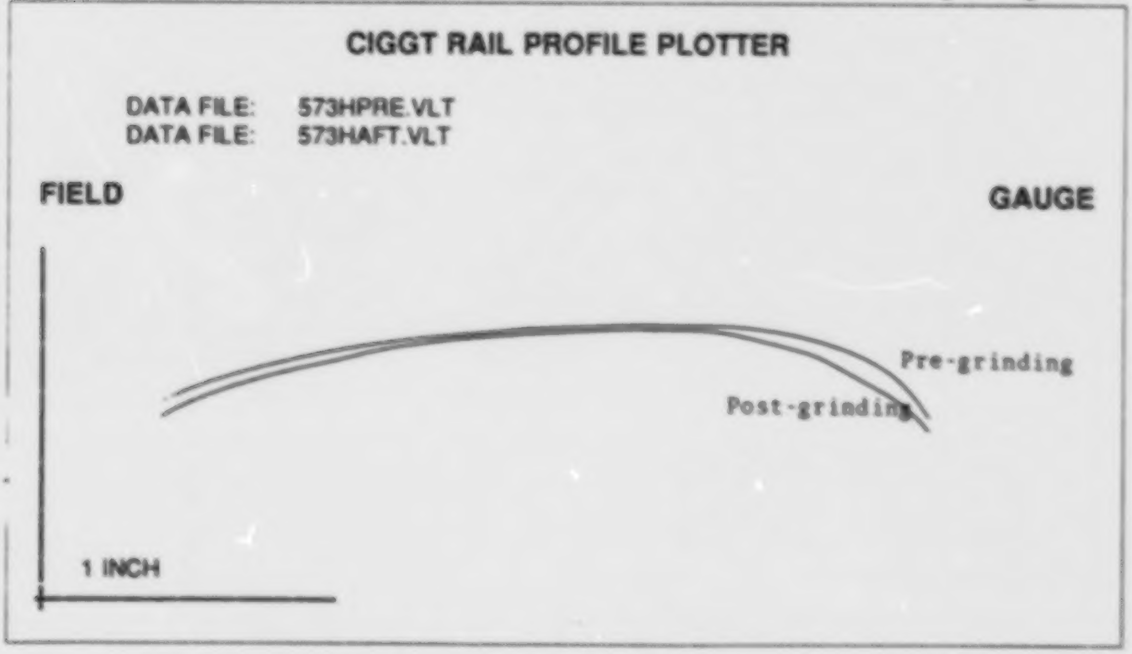


Figure C.52: Measured railhead profiles at test site 7.2 before and after grinding

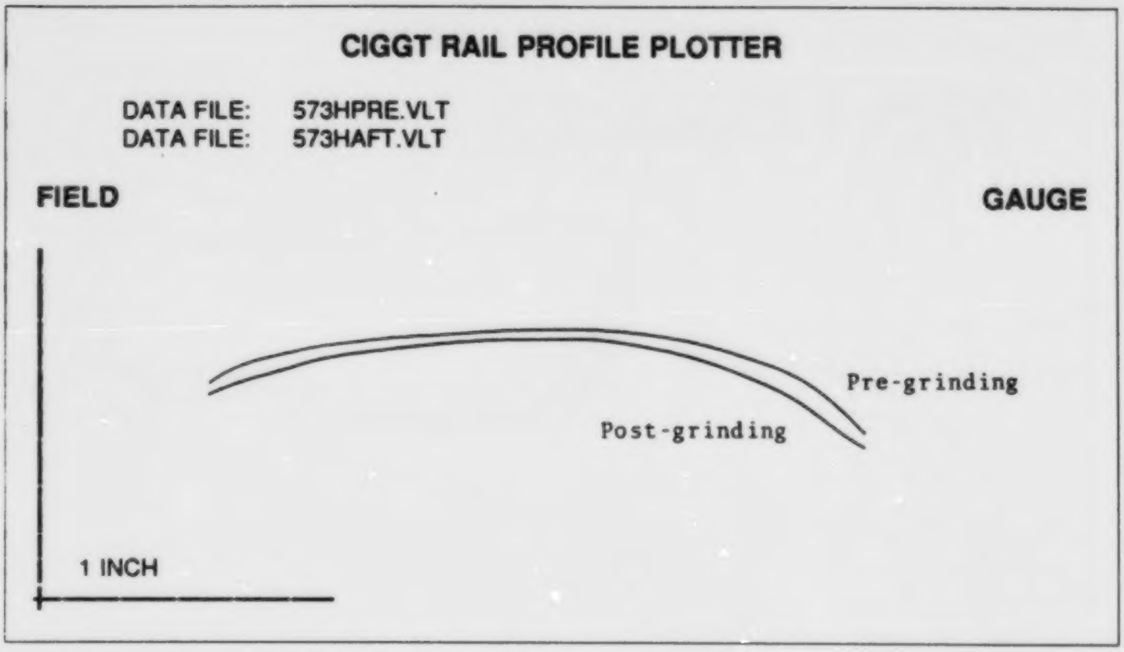


Figure C.53: Measured railhead profiles at test site 7.3 before and after grinding

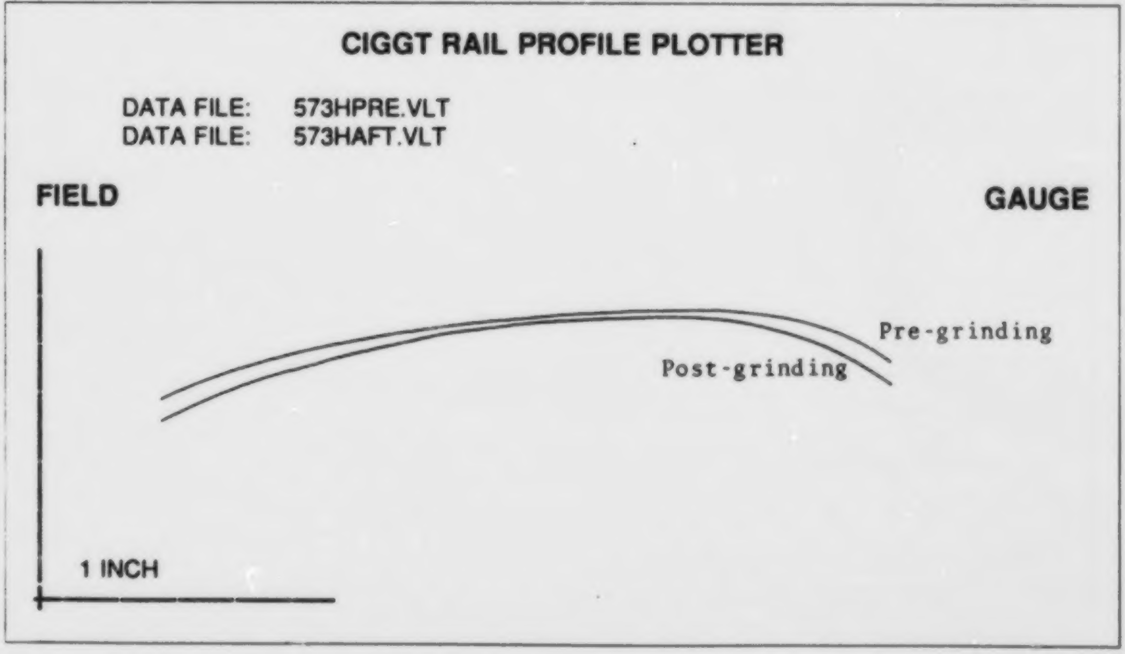


Figure C.54: Measured railhead profiles at test site 7.4 before and after grinding

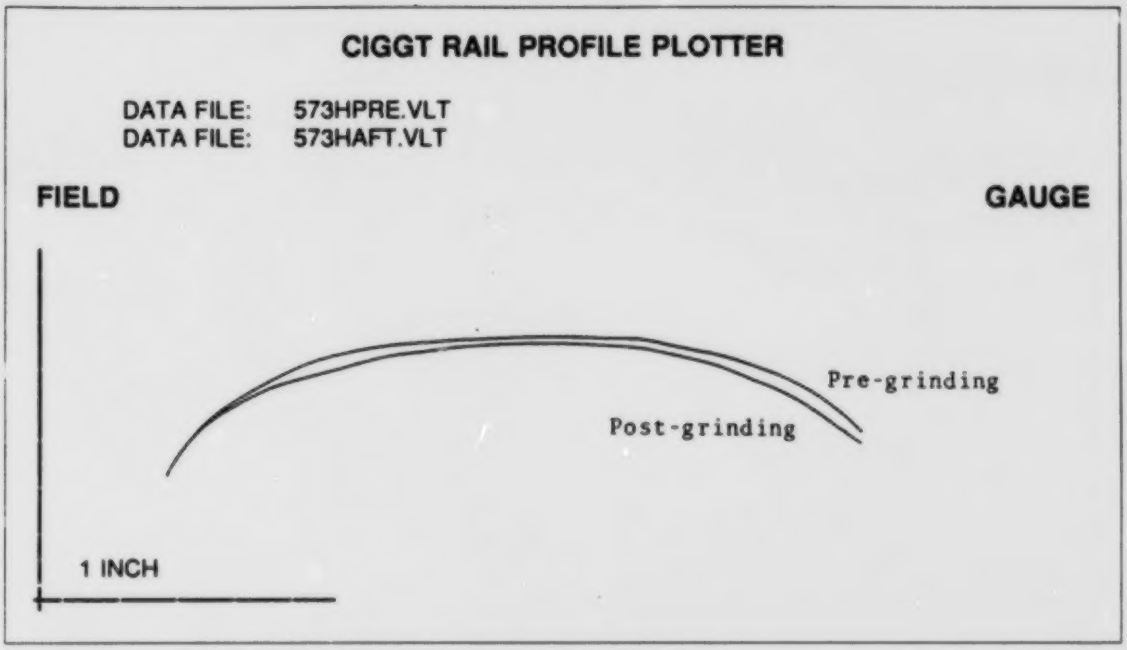


Figure C.55: Measured railhead profiles at test site 7.5 before and after grinding

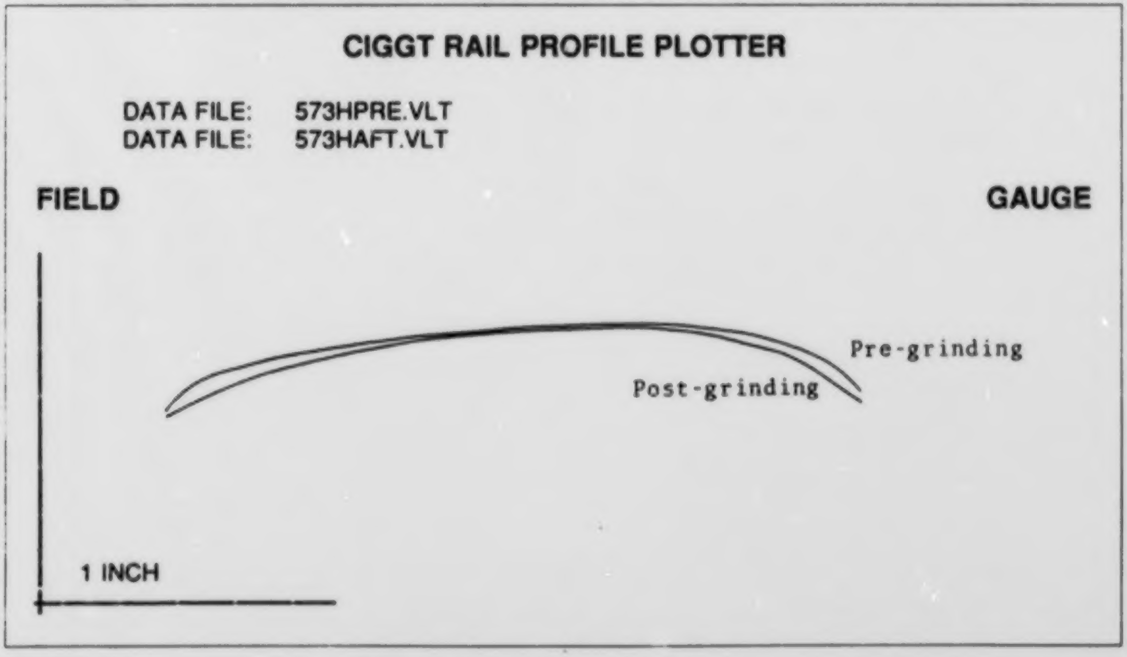


Figure C.56: Measured railhead profiles at test site 7.6 before and after grinding

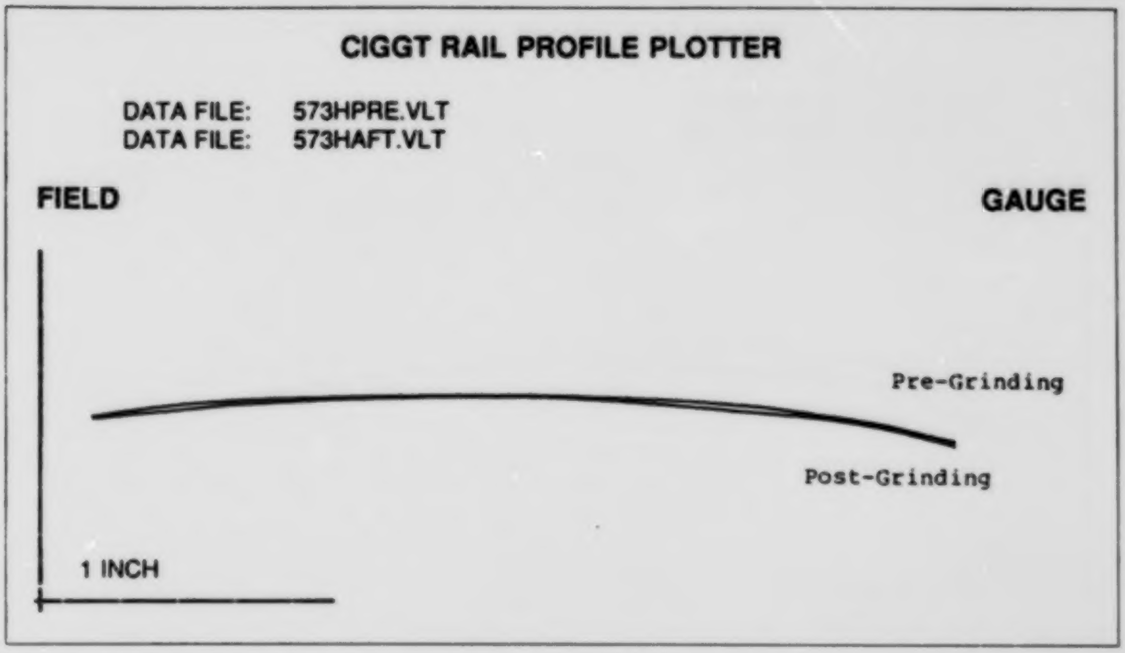


Figure C.57: Measured railhead profiles at test site 8.1 before and after grinding

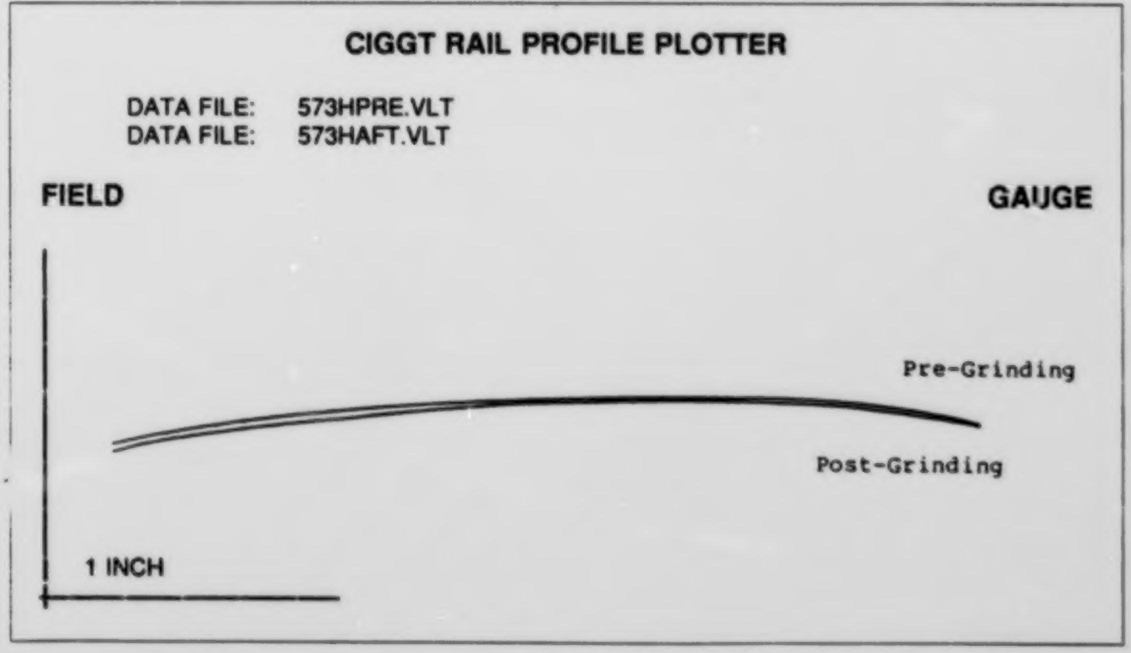


Figure C.58: Measured railhead profiles at test site 8.2 before and after grinding

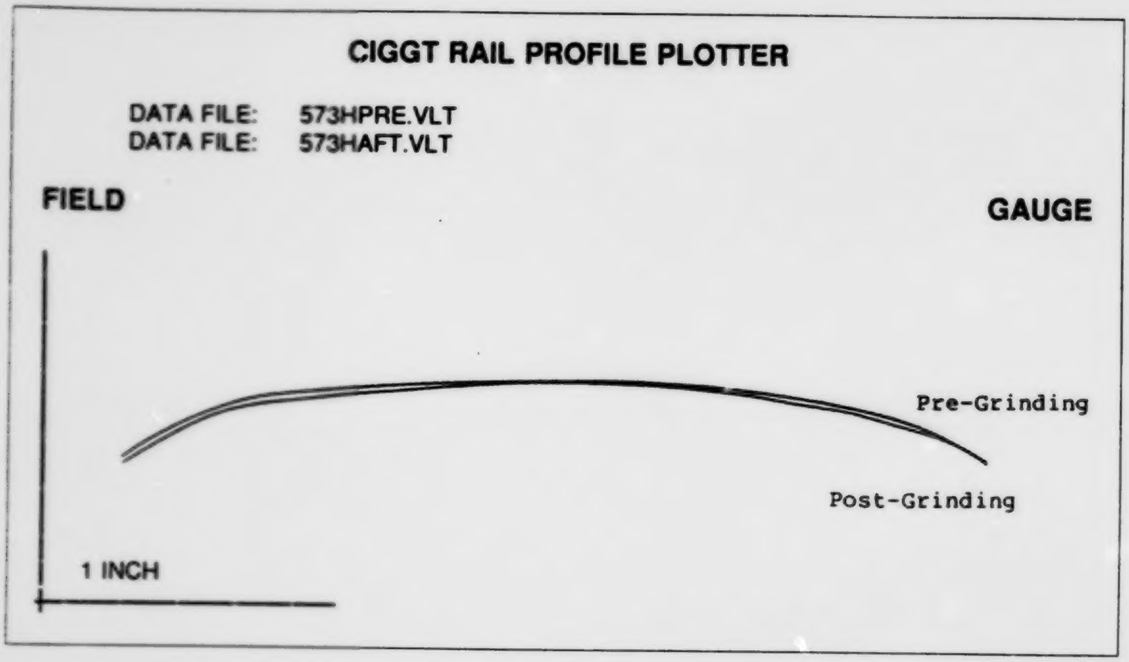


Figure C.59: Measured railhead profiles at test site 8.3 before and after grinding

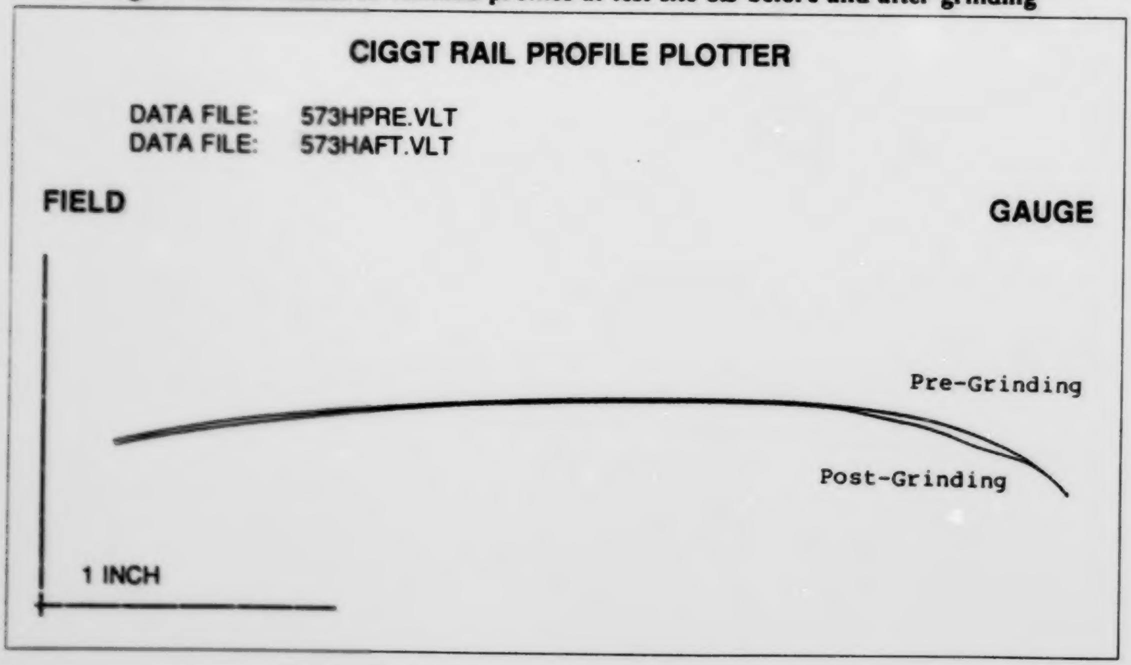


Figure C.60: Measured railhead profiles at test site 8.4 before and after grinding

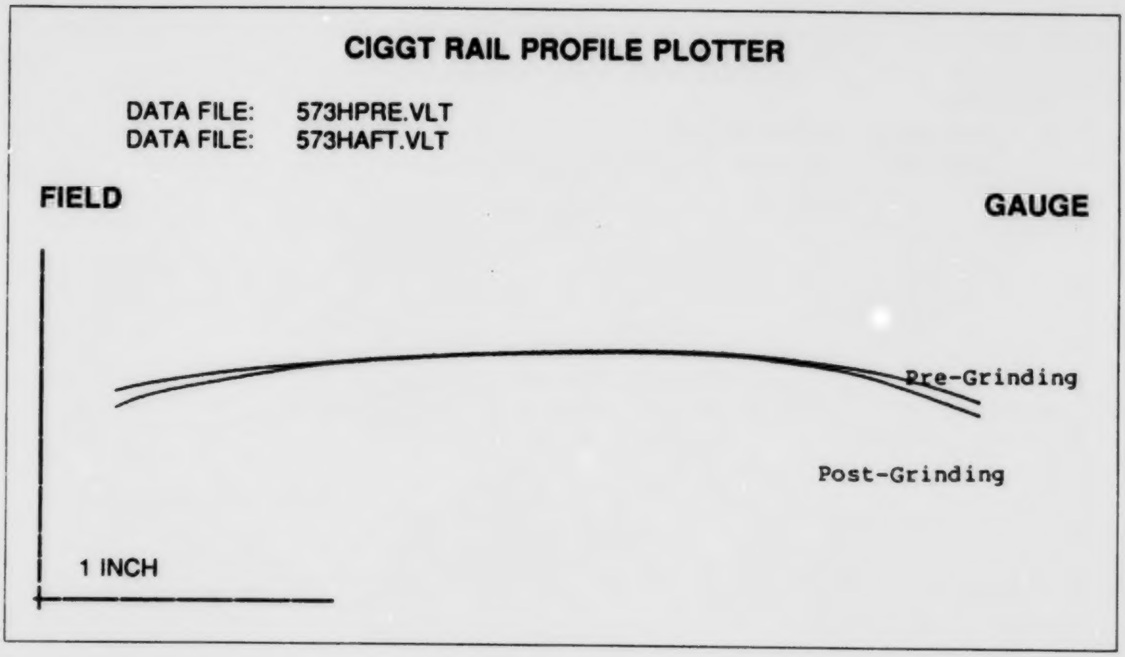


Figure C.61: Measured railhead profiles at test site 8.5 before and after grinding

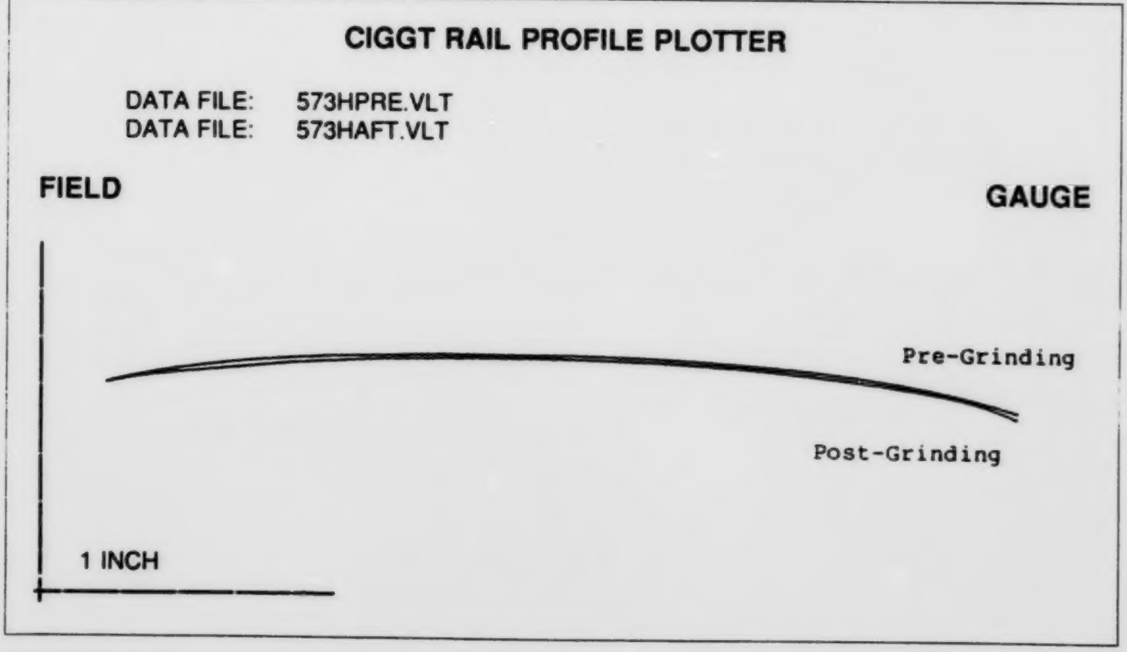


Figure C.62: Measured railhead profiles at test site 8.6 before and after grinding

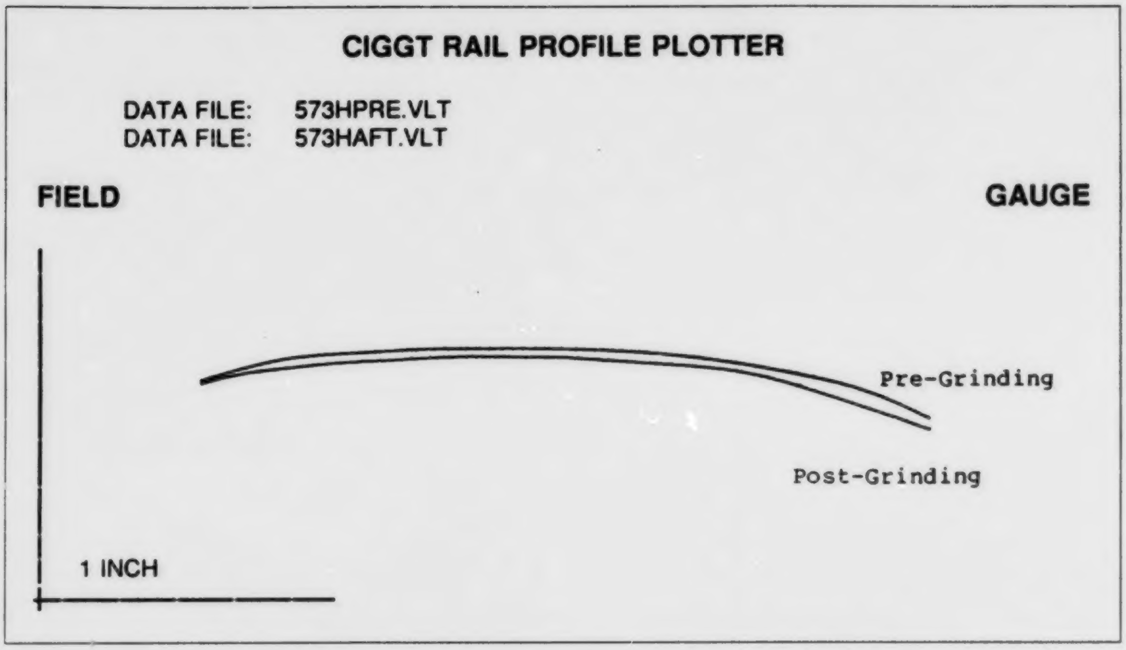


Figure C.63: Measured railhead profiles at test site 8.7 before and after grinding

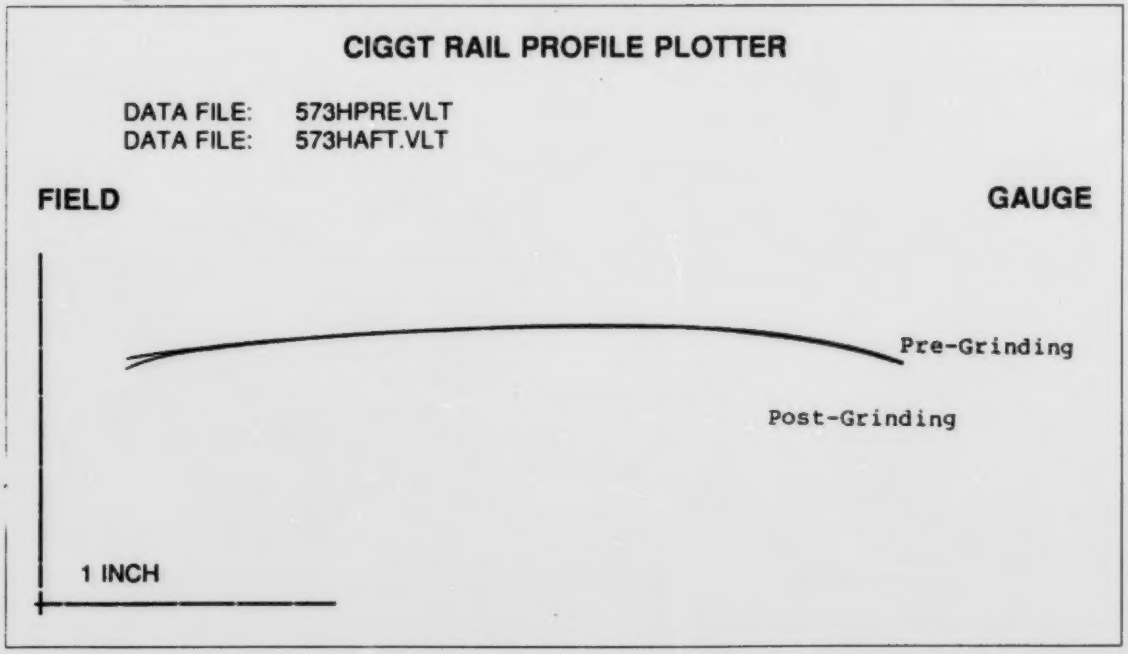


Figure C.64: Measured railhead profiles at test site 8.8 before and after grinding

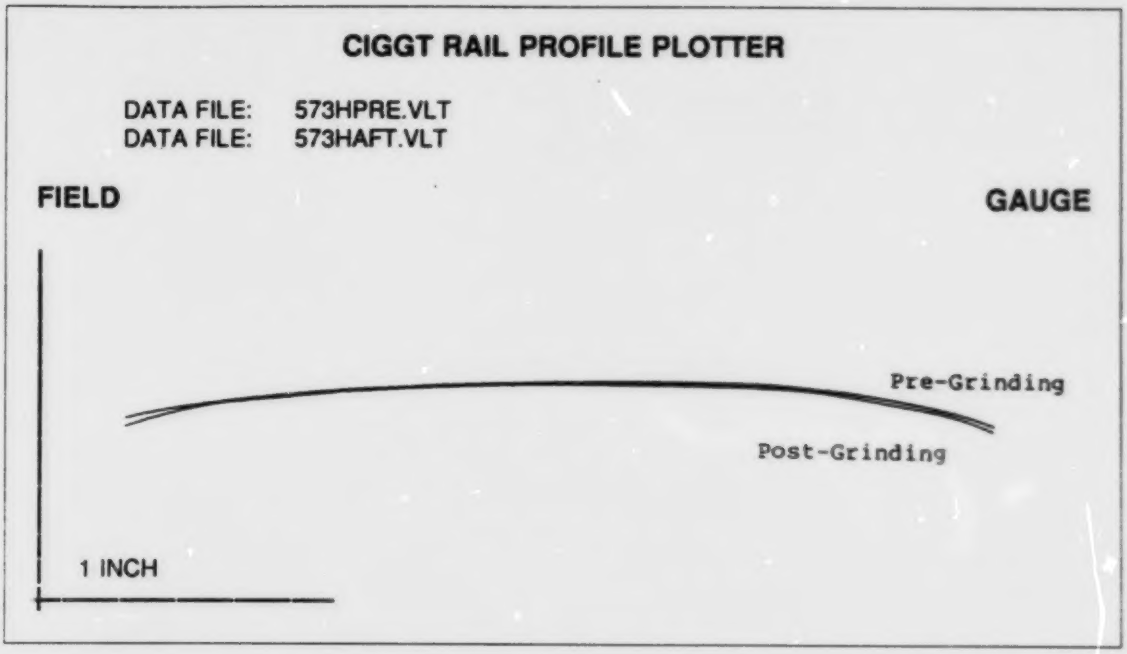


Figure C.65: Measured railhead profiles at test site 8.9 before and after grinding

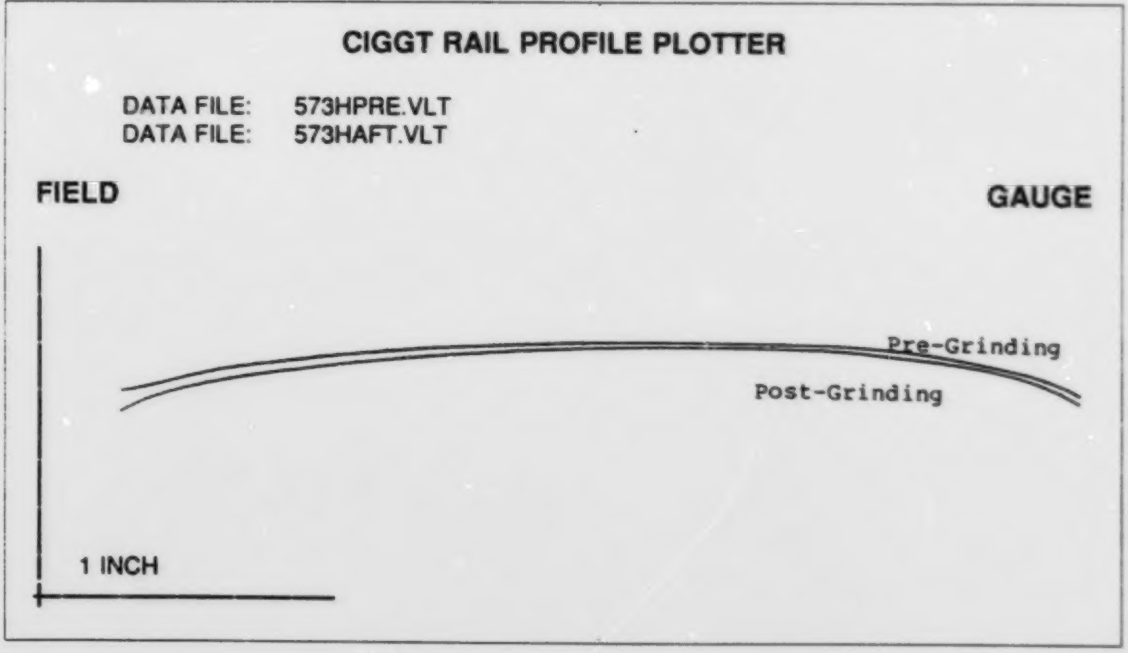


Figure C.66: Measured railhead profiles at test site 9.1 before and after grinding

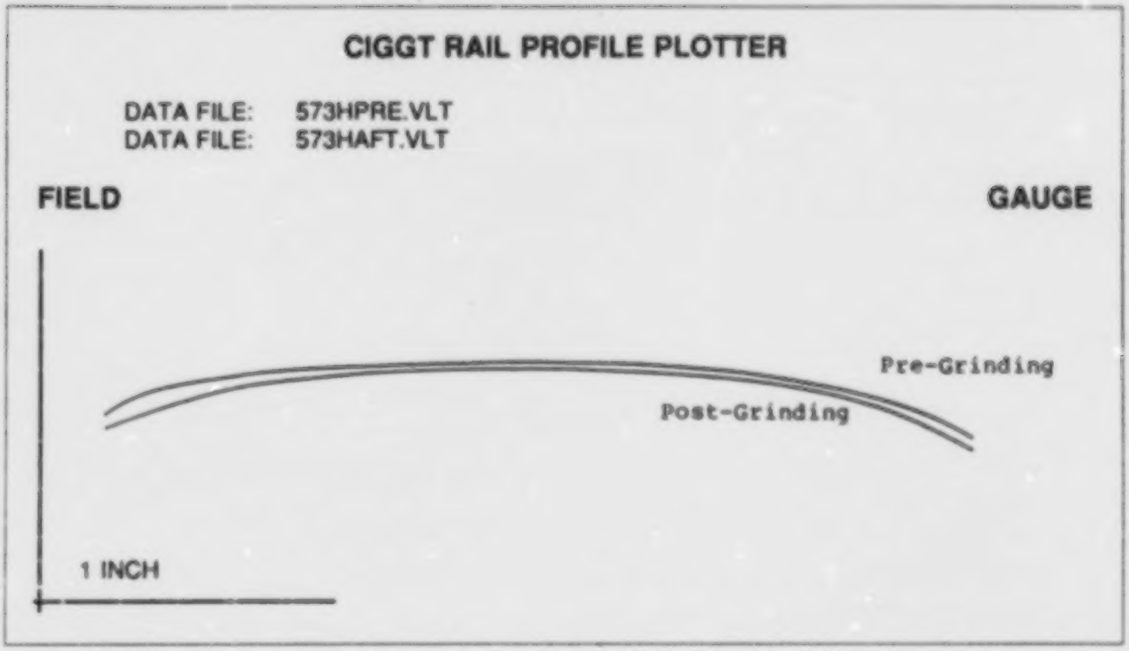


Figure C.67: Measured railhead profiles at test site 9.2 before and after grinding

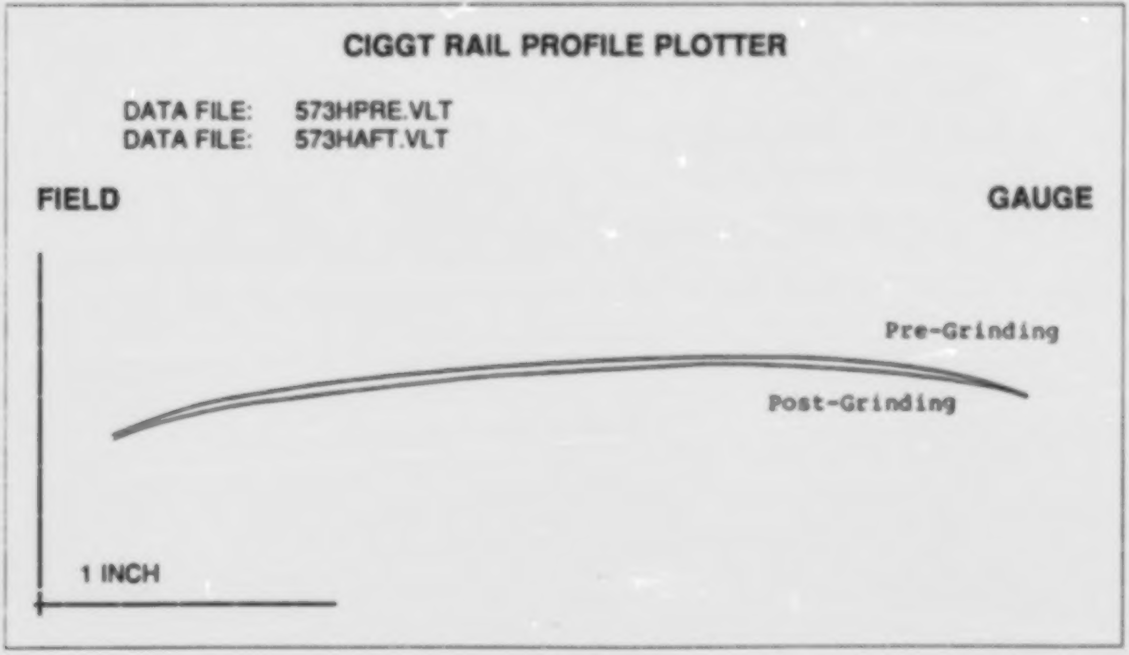


Figure C.68: Measured railhead profiles at test site 10.1 before and after grinding

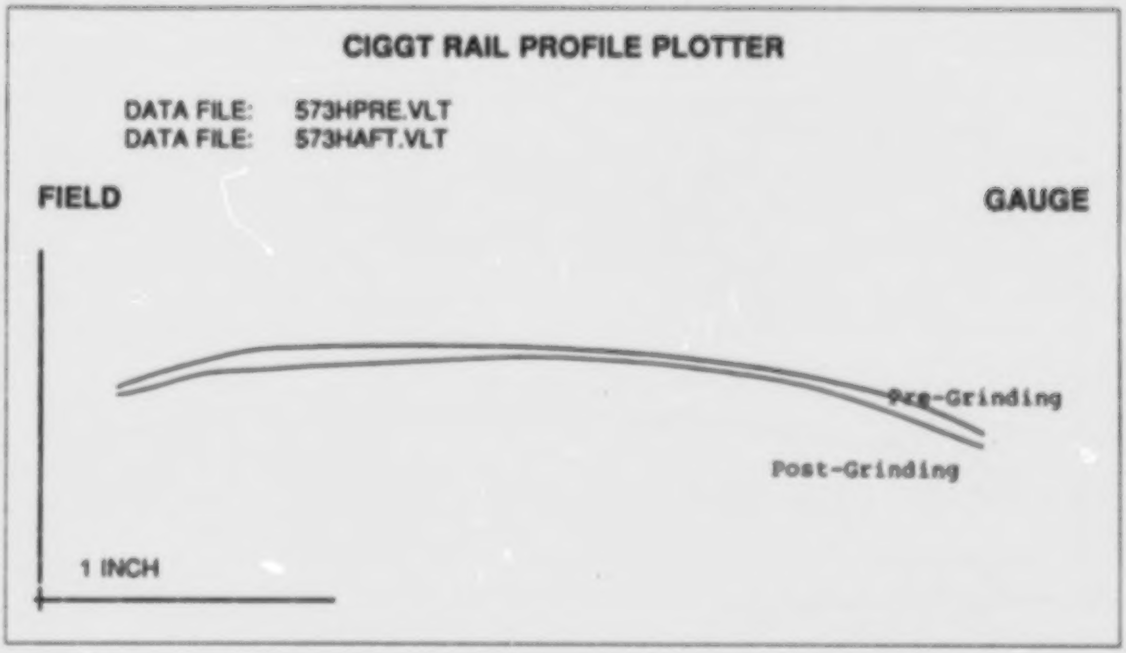


Figure C.69: Measured railhead profiles at test site 10.2 before and after grinding

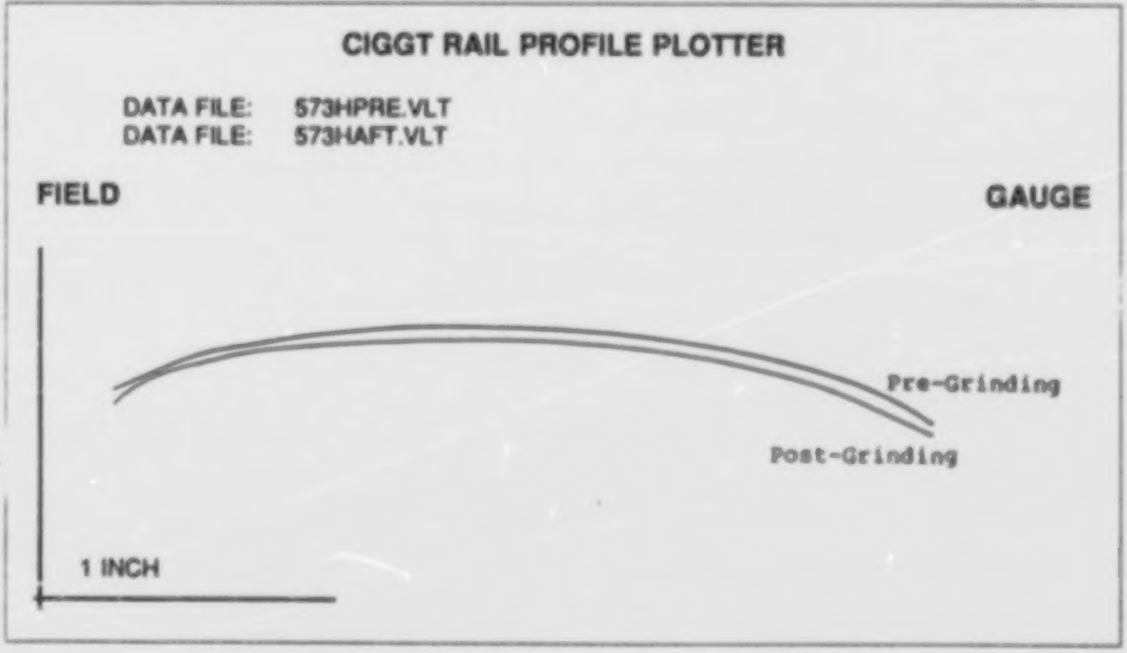


Figure C.70: Measured railhead profiles at test site 11.1 before and after grinding

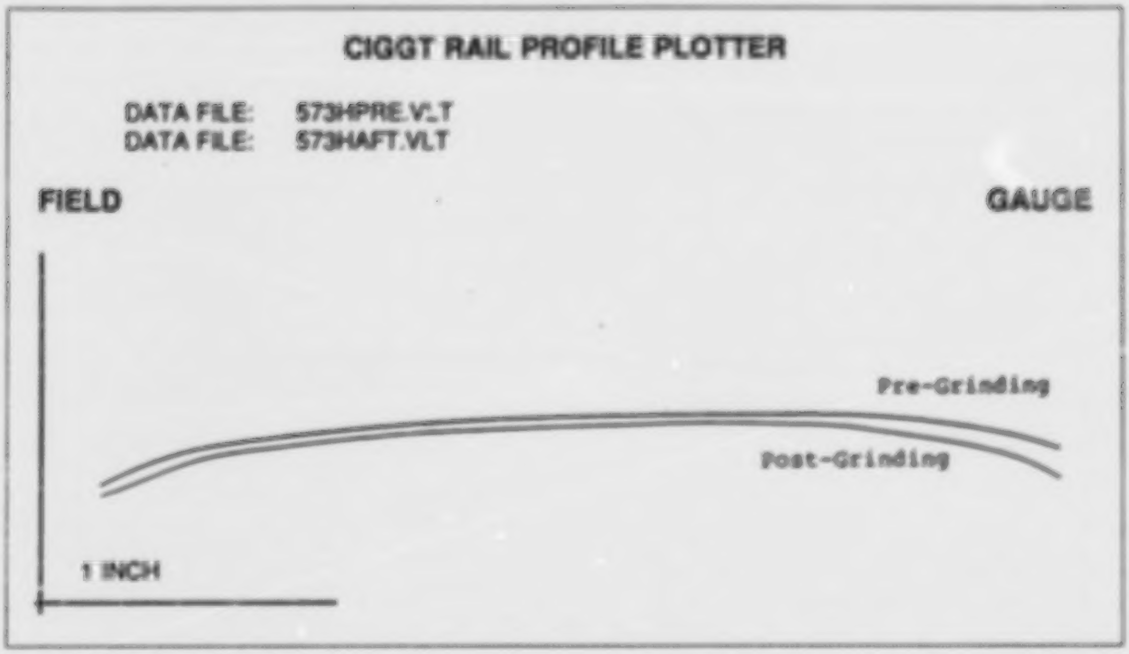


Figure C.71: Measured railhead profiles at test site 11.2 before and after grinding

APPENDIX D

PREVENTIVE MAINTENANCE GRINDING

DETAILS OF RAIL HEAD SURFACE CONDITIONS

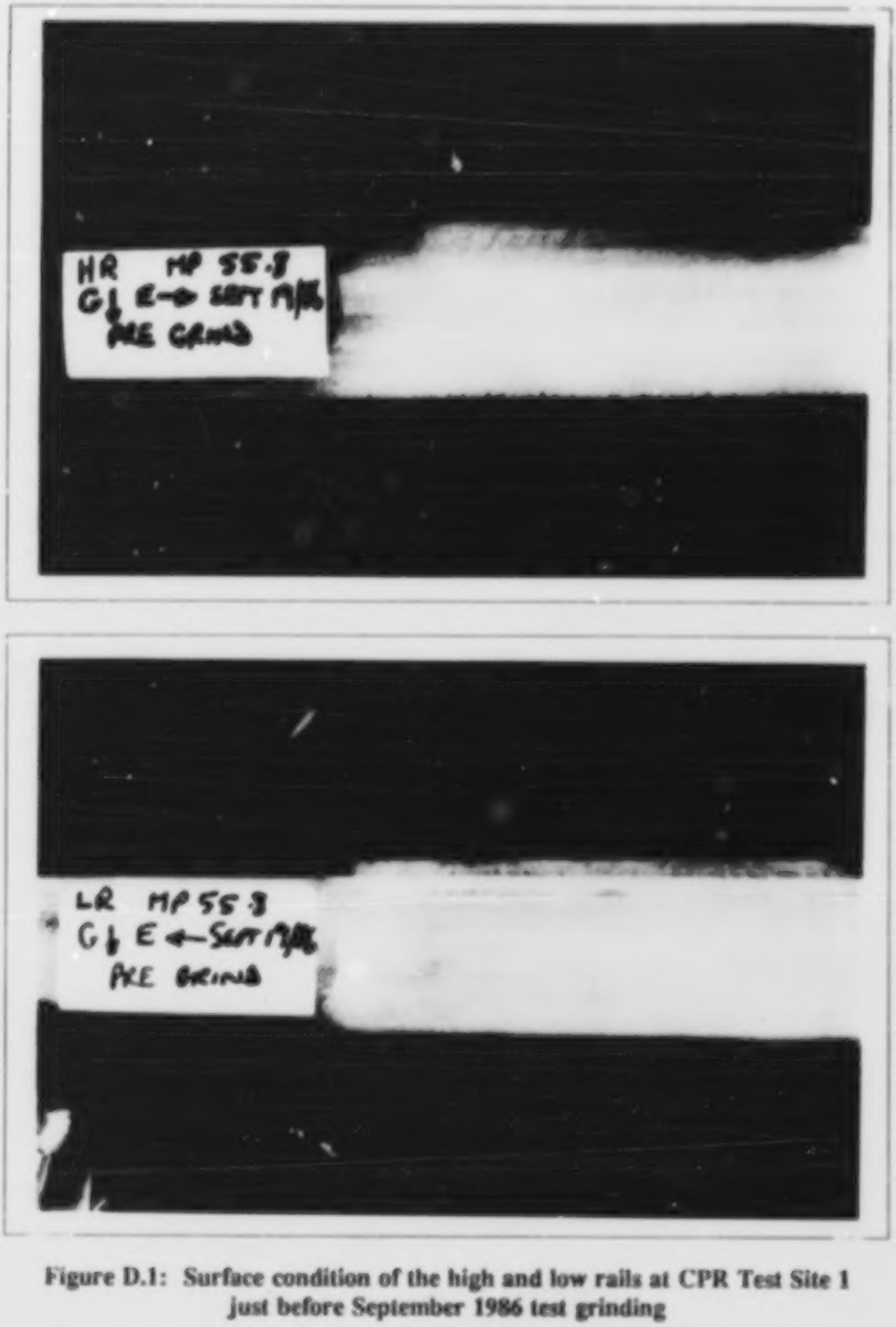

HR MP 55.8
G↓ E→ SEPT 17/86
PRE GRIND
LR MP 55.8
G↓ E← SEPT 17/86
PRE GRIND

Figure D.1: Surface condition of the high and low rails at CPR Test Site 1 just before September 1986 test grinding

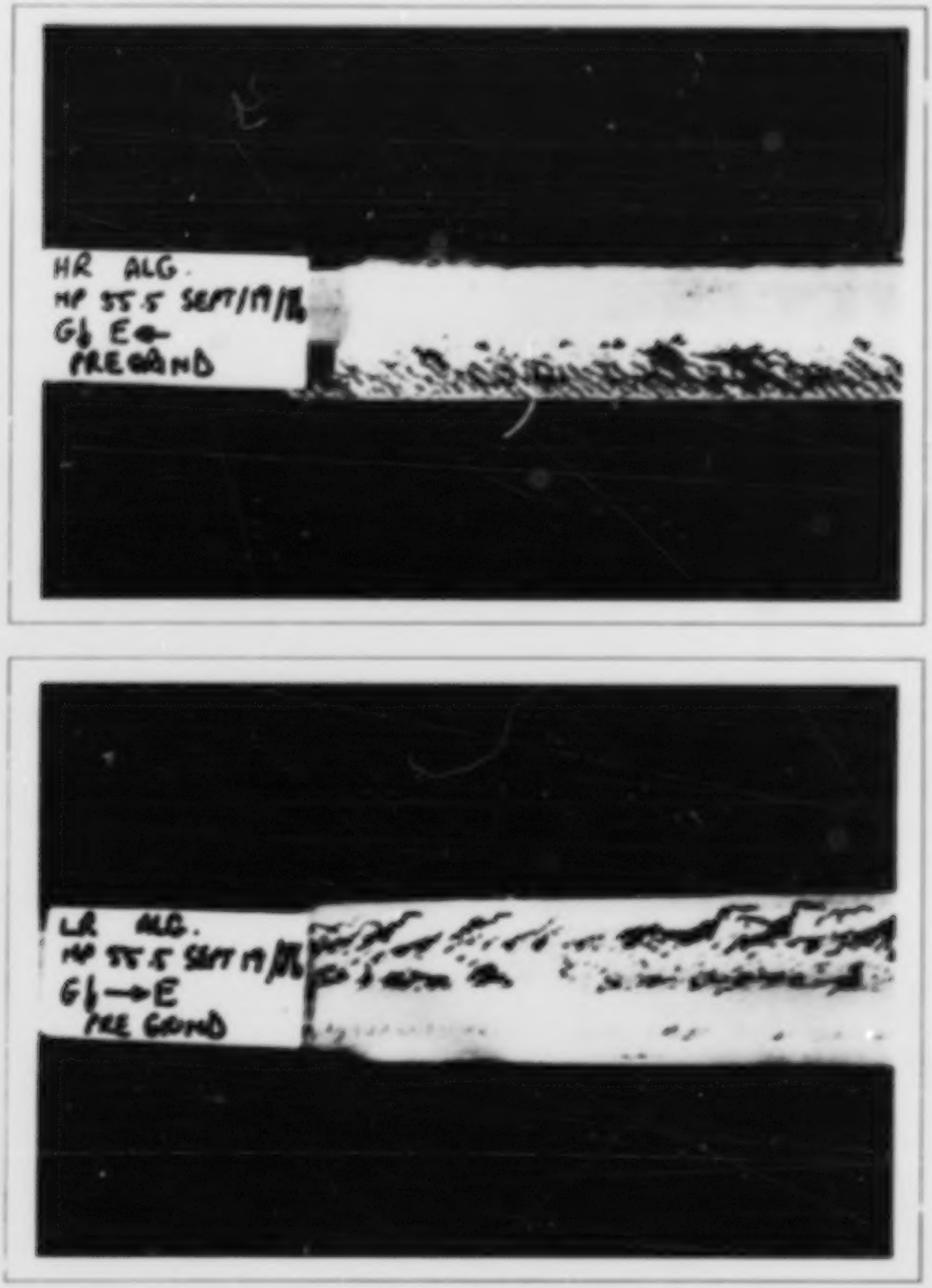

E
HR ALG.
MP 55.5 SEPT/19/86
G E←
PREGRIND
LR ALG.
MP 55.5 SEPT 19/86
G →E
PRE GRIND

Figure D.2: Surface condition of the high and low rails at CPR Test Site 2 just before September 1986 test grinding

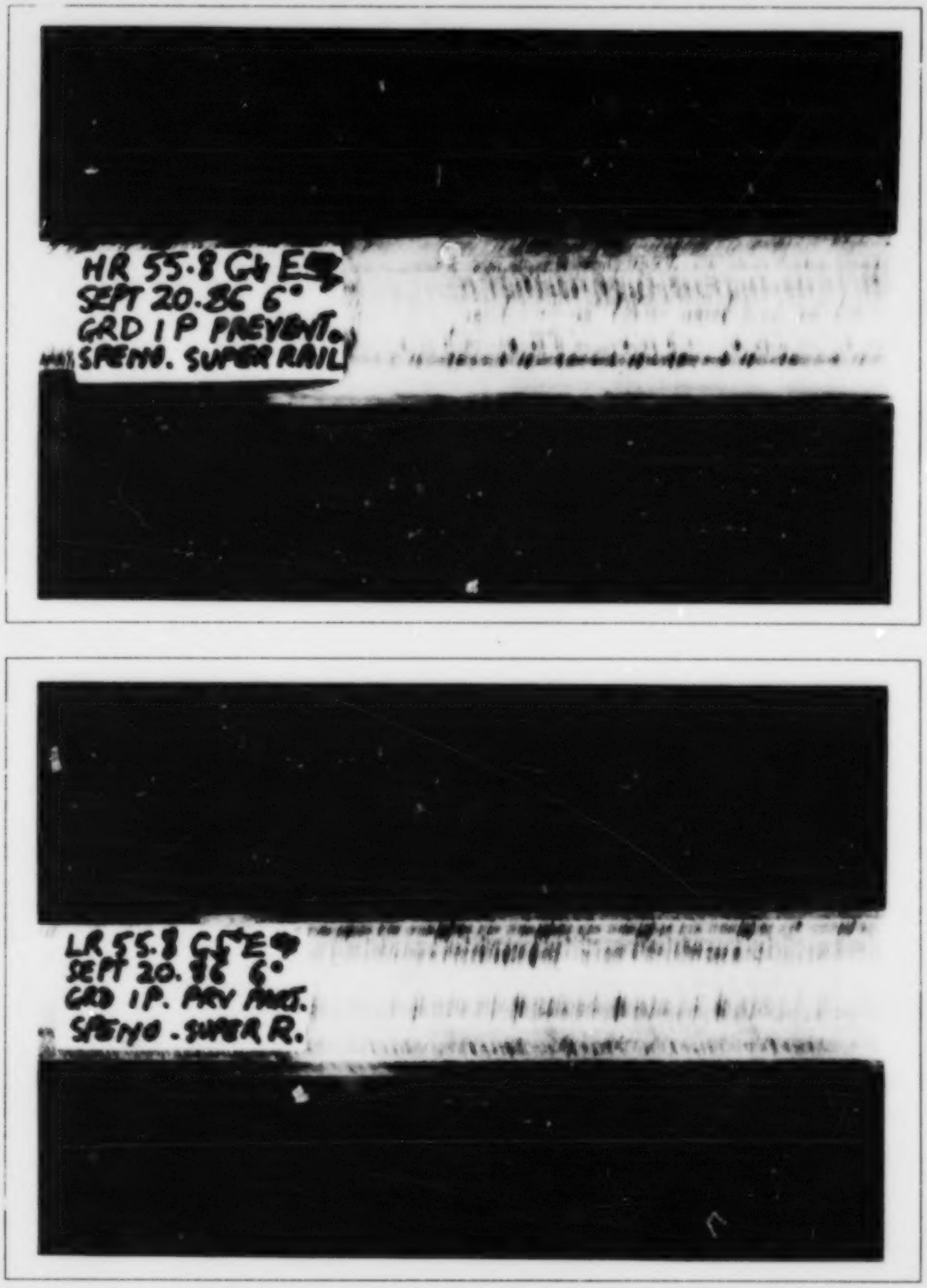

HR 55.8 G4 E
SEPT 20.86 6°
GRD 1 P PREVENT.
SPENO. SUPER RAIL
LR 55.8 G E
SEPT 20.86 6°
GRD 1P. PRV MNT.
SPENO. SUPER R.

Figure D.3: Surface condition of the high and low rails at CPR Test Site 1 after September 1986 test grinding

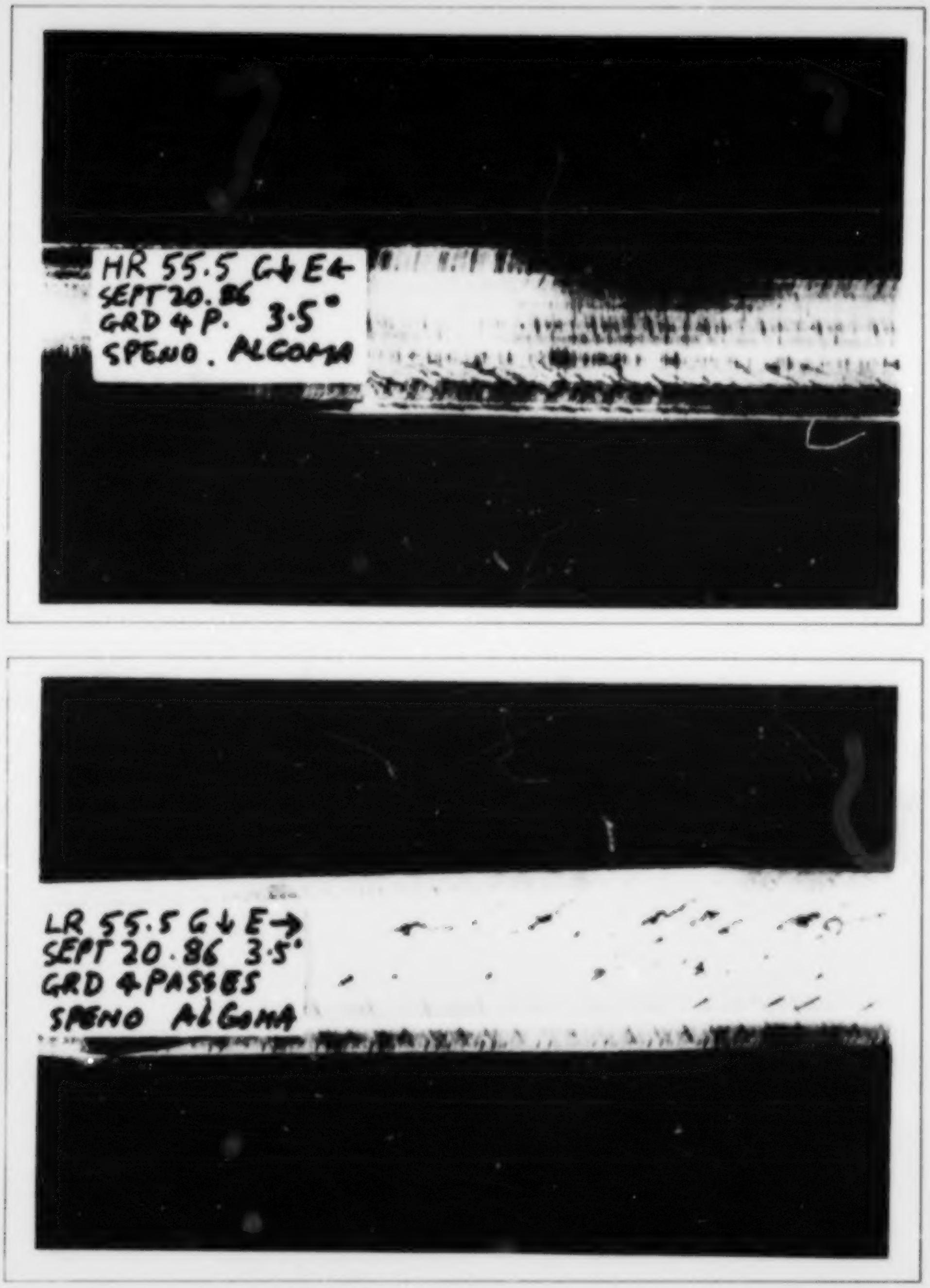

HR 55.5 G↓E←
SEPT 20.86
GRD 4 P. 3.5°
SPENO . ALGOMA
LR 55.5 G↓E→
SEPT 20.86 3.5°
GRD 4 PASSES
SPENO ALGOMA

Figure D.4: Surface condition of the high and low rails at CPR Test Site 2 after September 1986 test grinding

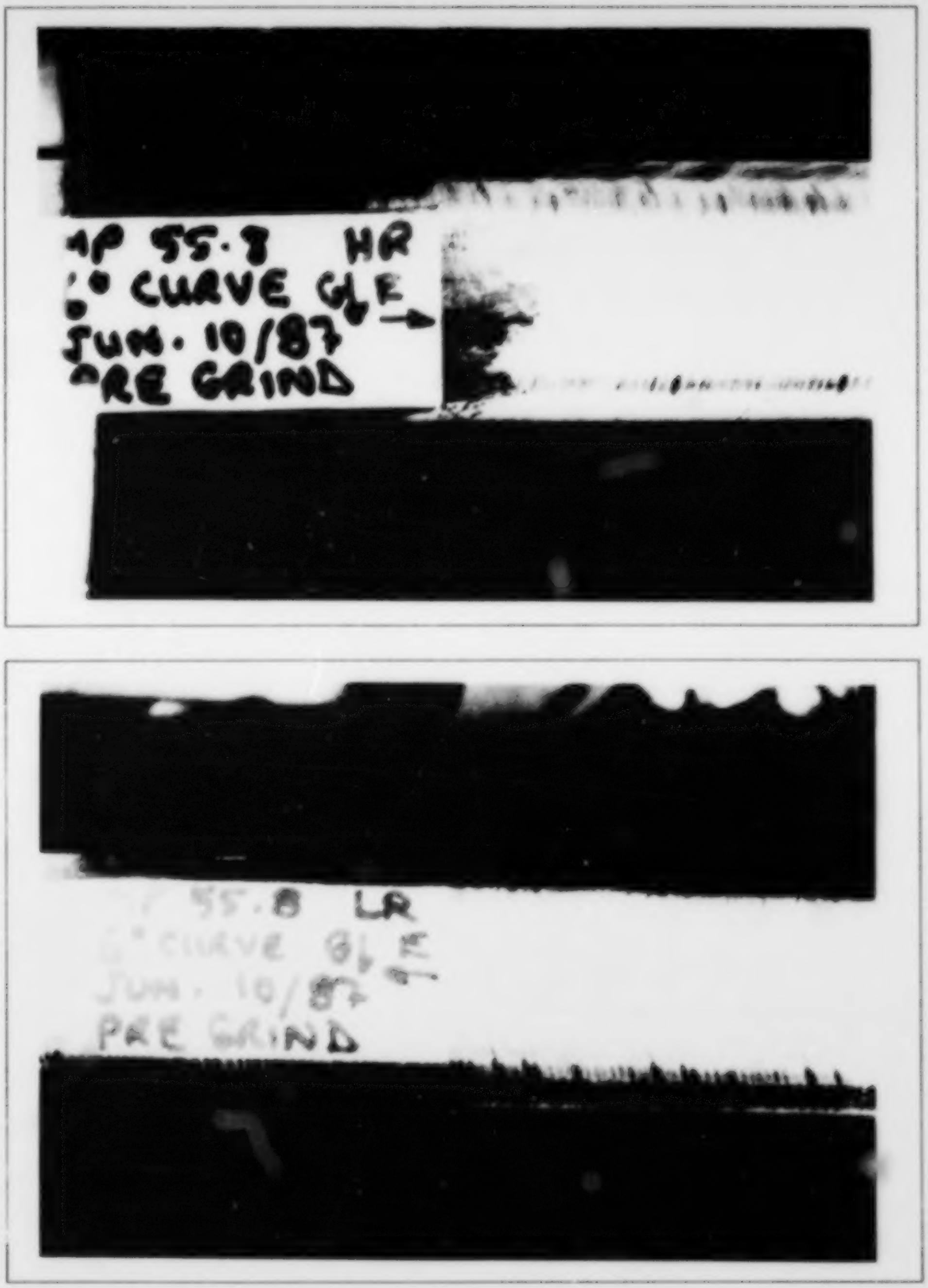

MP 55·8 HR
CURVE GLE
JUN. 10/87
PRE GRIND
55.8 LR
CURVE GLE
JUN. 10/87
PRE GRIND

Figure D.5: Surface condition of the high and low rails at CPR Test Site 1 just before June 1987 test grinding

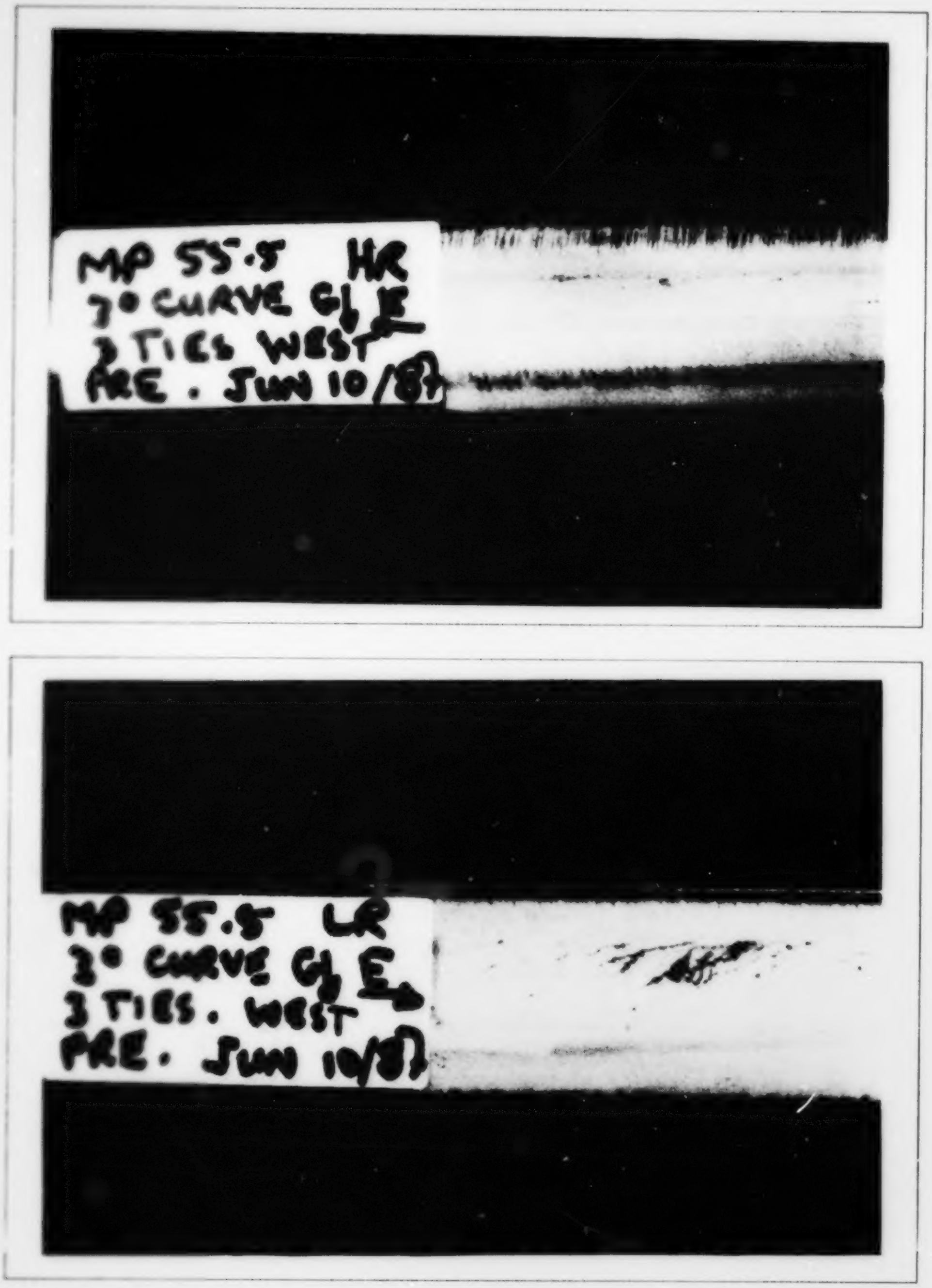

MP 55.5 HR
7° CURVE G1 E
3 TIES WEST
PRE. JUN 10/87
MP 55.5 LR
3° CURVE G1 E
3 TIES. WEST
PRE. JUN 10/87

Figure D.6: Surface condition of the high and low rails at CPR Test Site 2 just before June 1987 test grinding

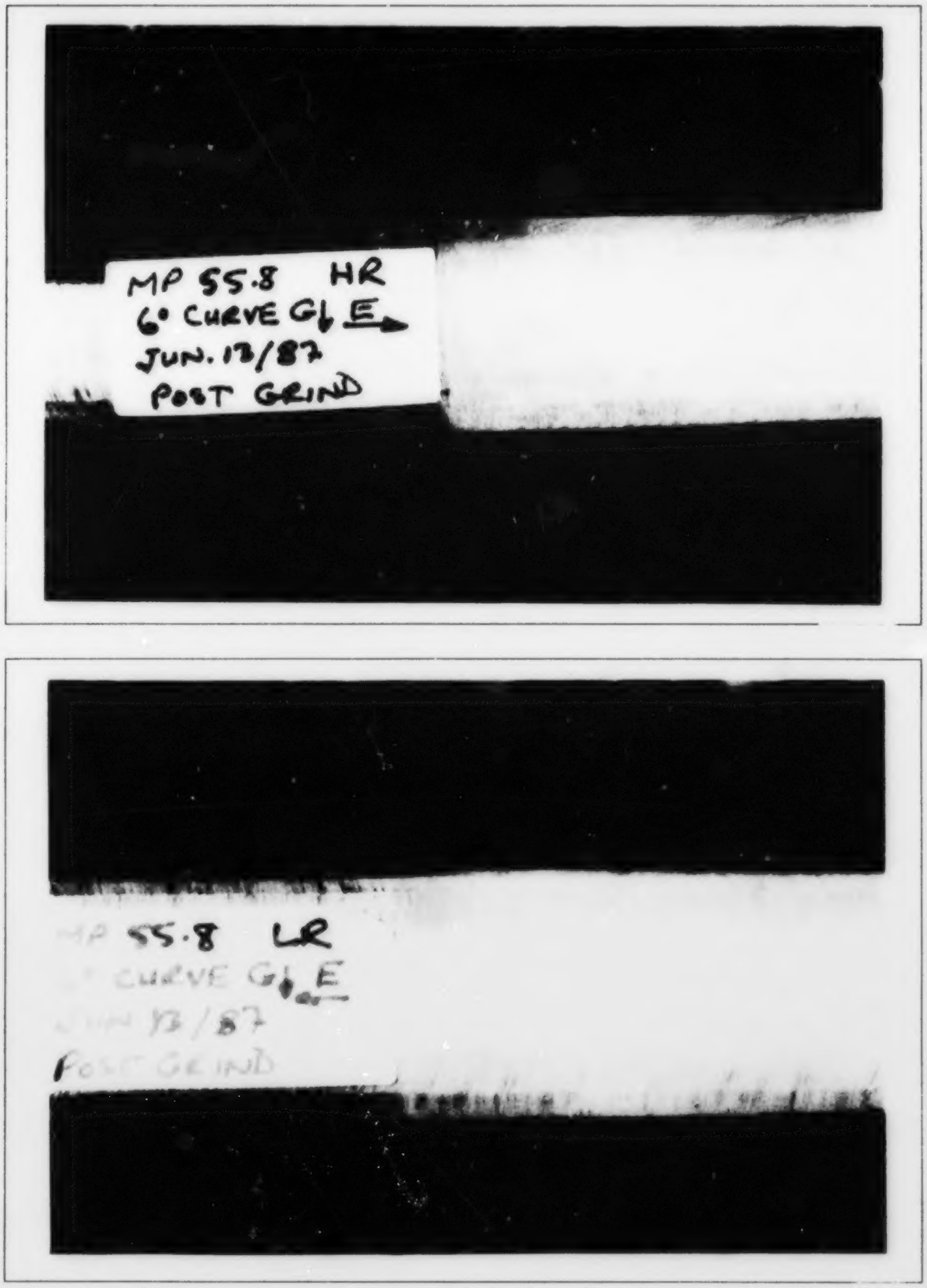

MP 55.8 HR
6° CURVE G℄ E
JUN. 13/87
POST GRIND
MP 55.8 LR
CURVE G℄ E
JUN 13/87
POST GRIND

Figure D.7: Surface condition of the high and low rails at CPR Test Site 1 after June 1987 test grinding

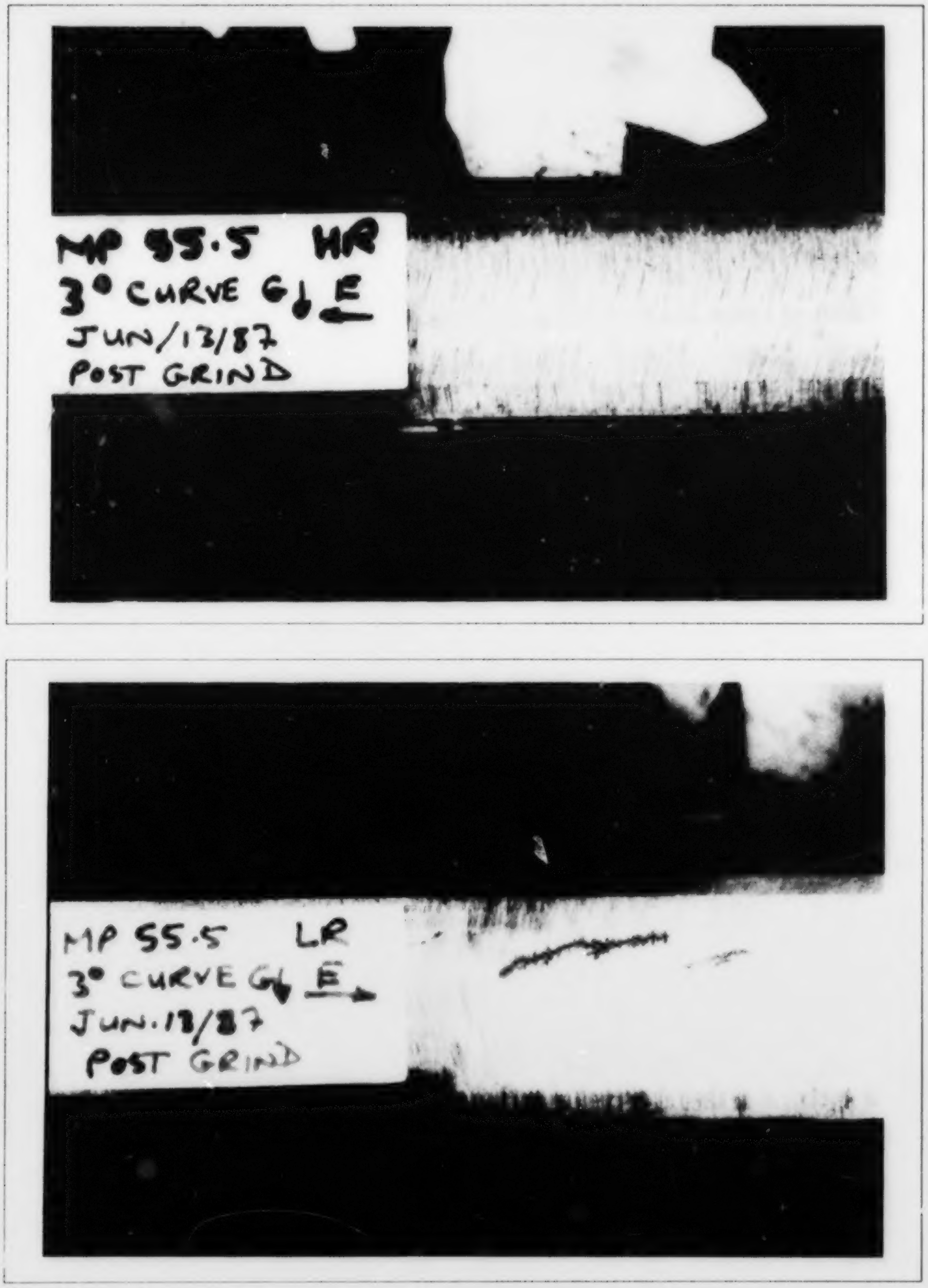

MP 55.5 HR
3° CURVE G↓ E←
JUN/13/87
POST GRIND
MP 55.5 LR
3° CURVE G↓ E→
JUN.13/87
POST GRIND

Figure D.8: Surface condition of the high and low rails at CPR Test Site 2 after June 1987 test grinding

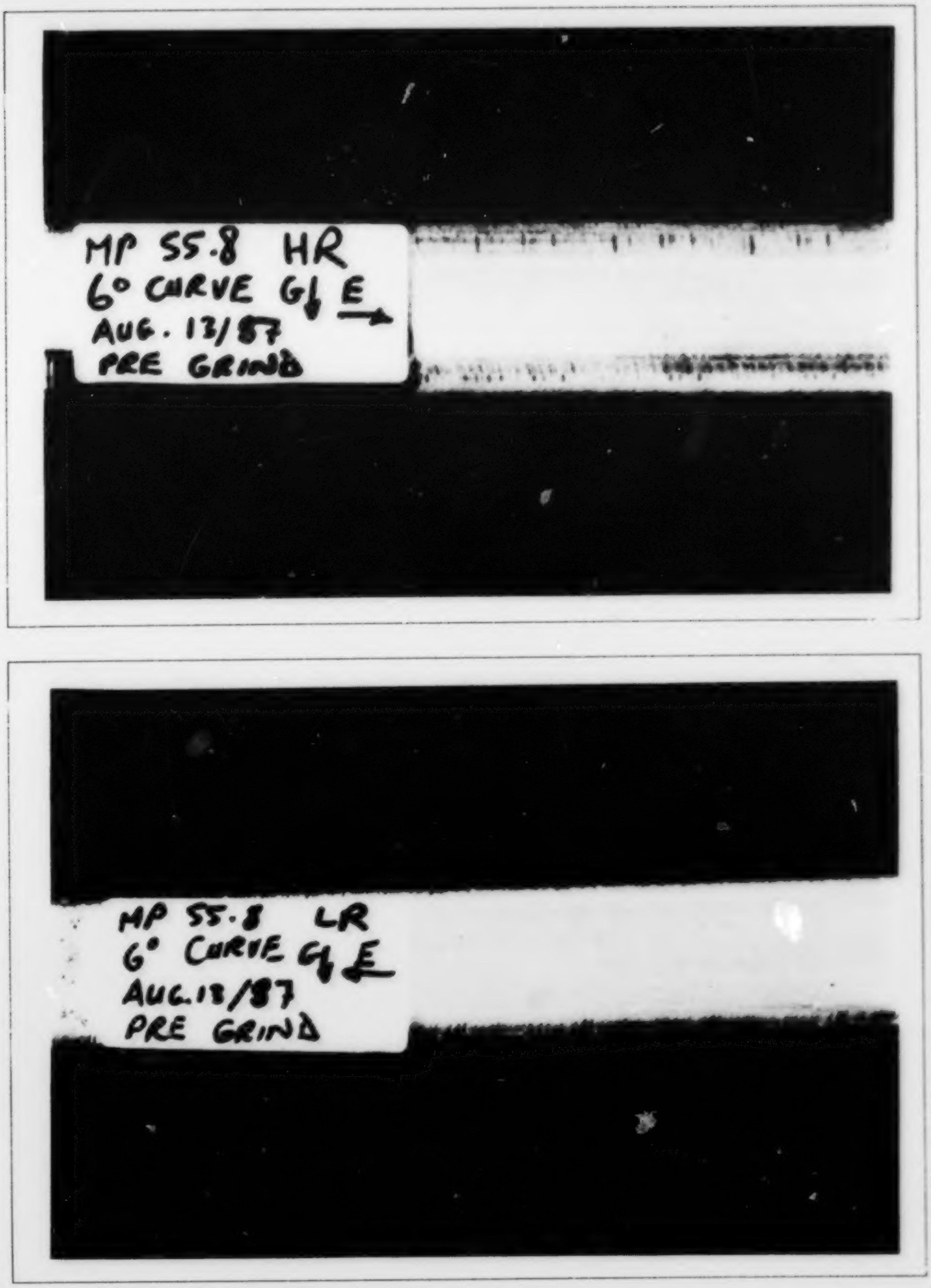

MP 55.8 HR
6° CURVE G↓ E →
AUG. 13/87
PRE GRIND
MP 55.8 LR
6° CURVE G↓ E
AUG.13/87
PRE GRIND

Figure D.9: Surface condition of the high and low rails at CPR Test Site 1 just before August 1987 test grinding

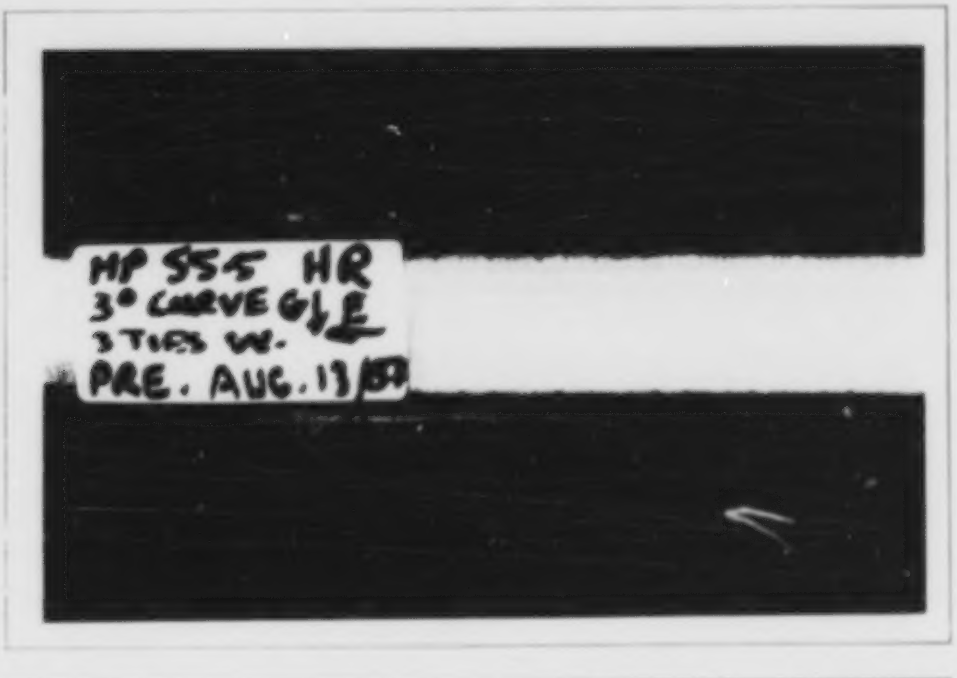

MP 55.5 HR
3° CURVE G E
3 TIES W.
PRE. AUG. 13/87
MP 55.5 LR
3° CURVE G E
PRE. AUG. 13/87

Figure D.10: Surface condition of the high and low rails at CPR Test Site 2 just before August 1987 test grinding

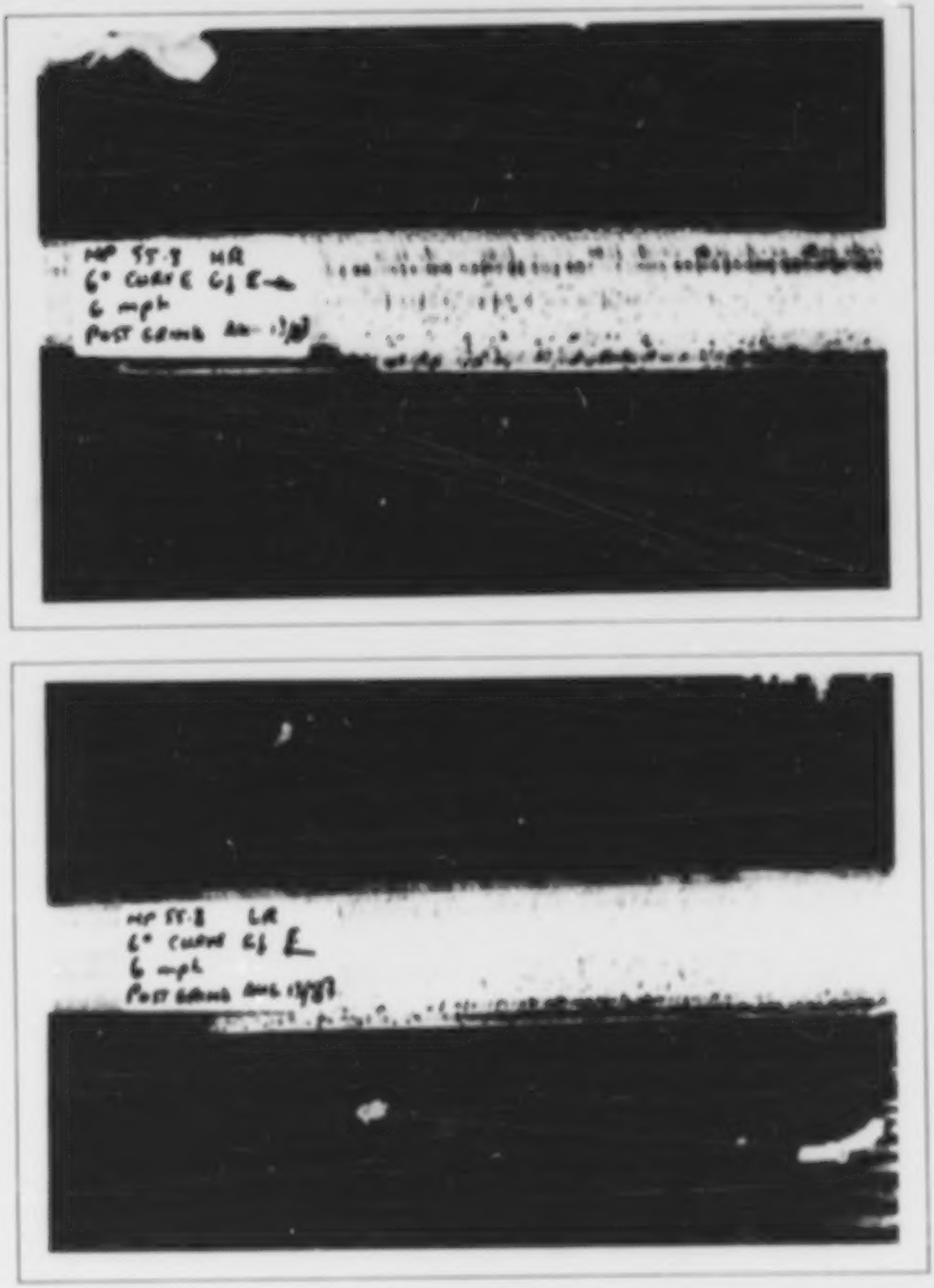

MP 55.8 HR
6° CURVE 6½ E→
6 mph
POST GRIND AUG 1987
MP 55.8 LR
6° CURVE 6½ E
6 mph
POST GRIND AUG 1987

Figure D.11: Surface condition of the high and low rails at CPR Test Site 1 after August 1987 test grinding

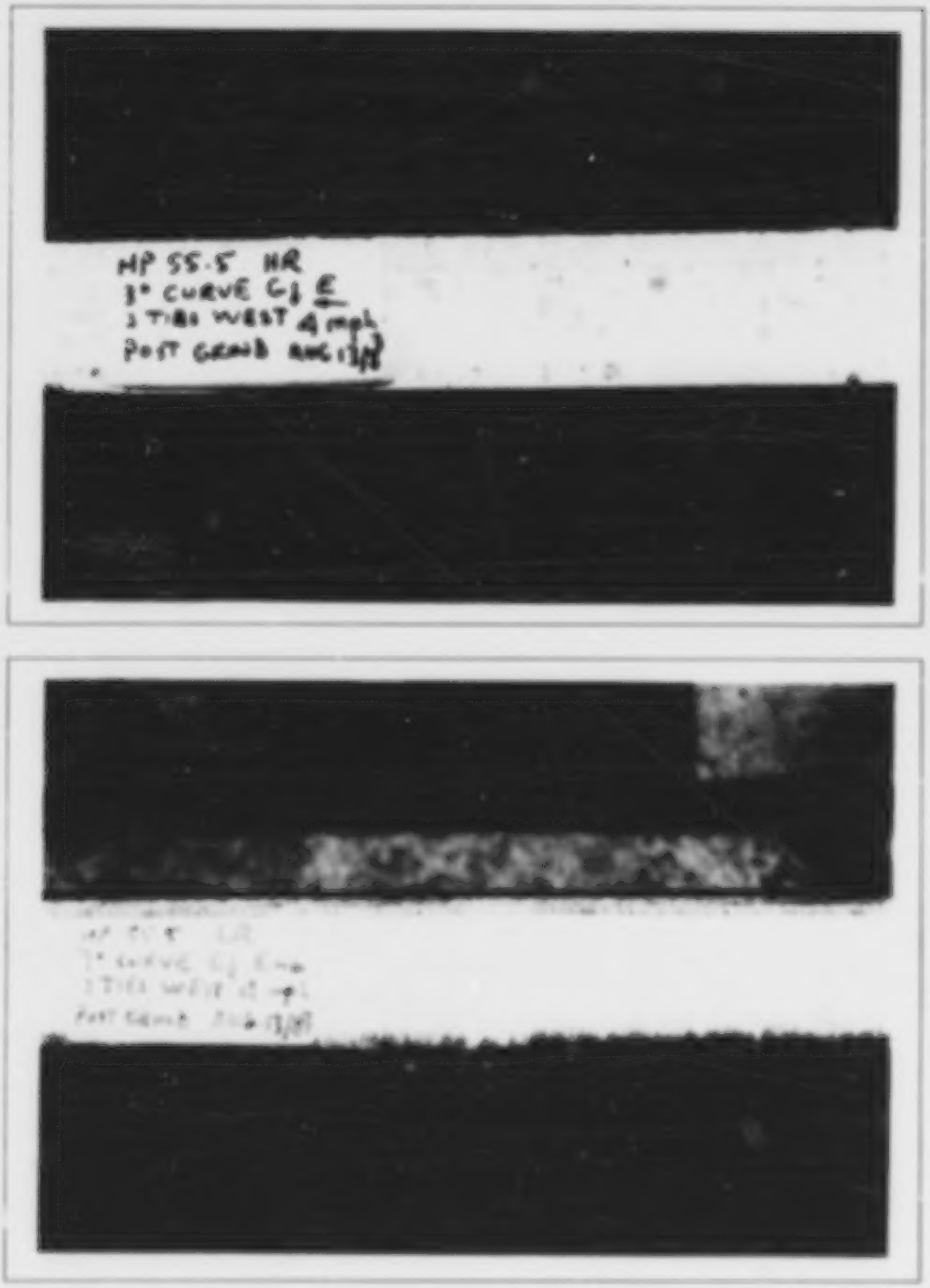

HP 55.5 HR
3° CURVE C/L E
2 TIBS WEST 4 mph
POST GRIND AUG 13/87
HP 55.5 LR
3° CURVE C/L E
2 TIBS WEST 4 mph
POST GRIND AUG 13/87

Figure D.12: Surface condition of the high and low rails at CPR Test Site 2 after August 1987 test grinding

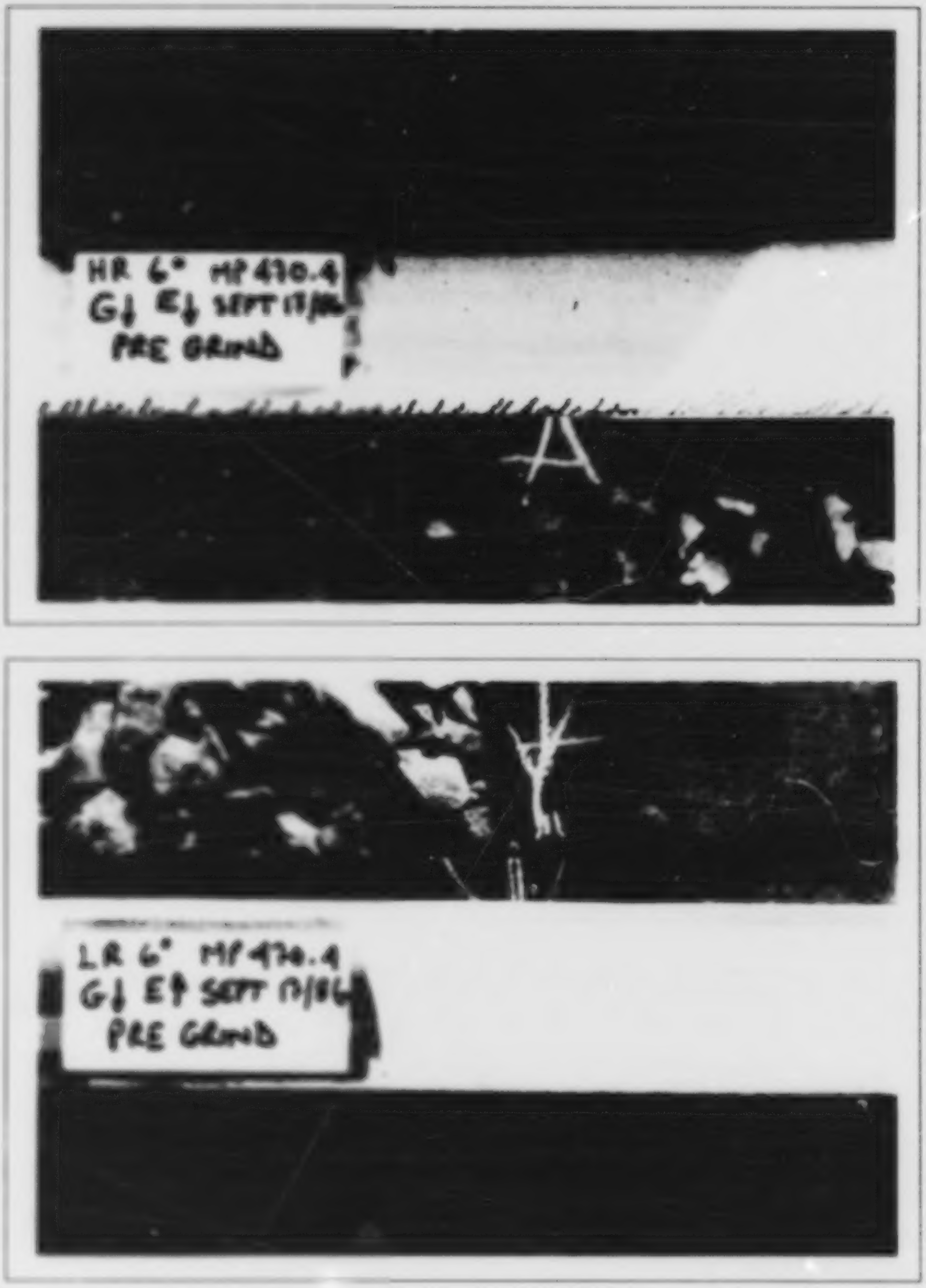
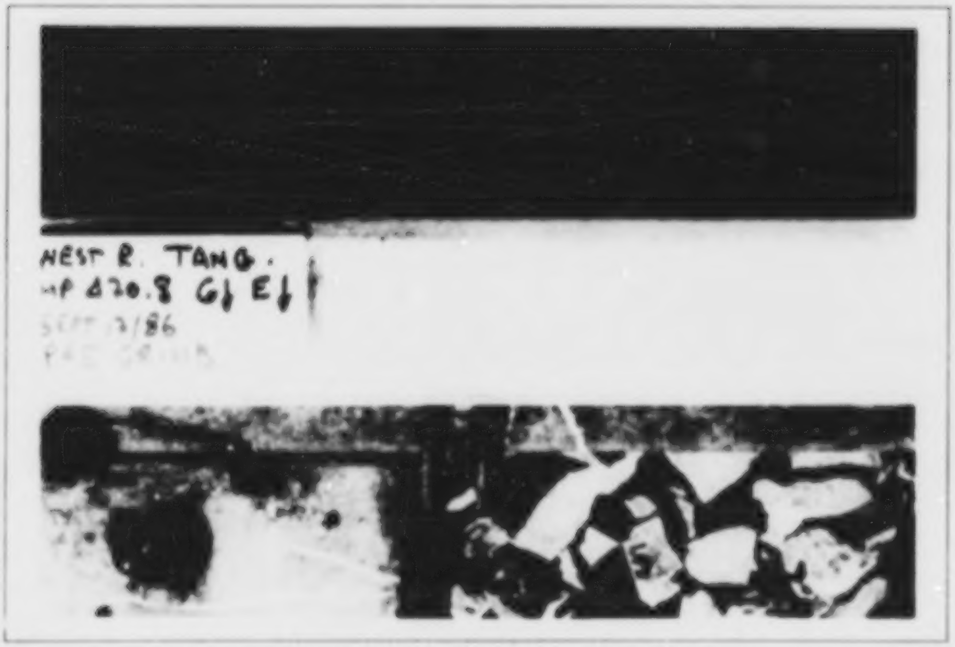

HR 6° MP 470.4
G↓ E↓ SEPT 17/86
PRE GRIND
A
LR 6° MP 470.4
G↓ E↑ SEPT 17/86
PRE GRIND

Figure D.13: Surface condition of the high and low rails at BCR Test Site 1 before September 1986 test grinding


WEST R. TANG.
MP 220.8 G↓ E↓
SEPT 12/86
PRE GRIND

NO PHOTOGRAPH WAS TAKEN OF THE EAST RAIL BEFORE GRINDING

Figure D.14: Surface condition of the west rail at BCR Test Site 2 before September 1986 test grinding

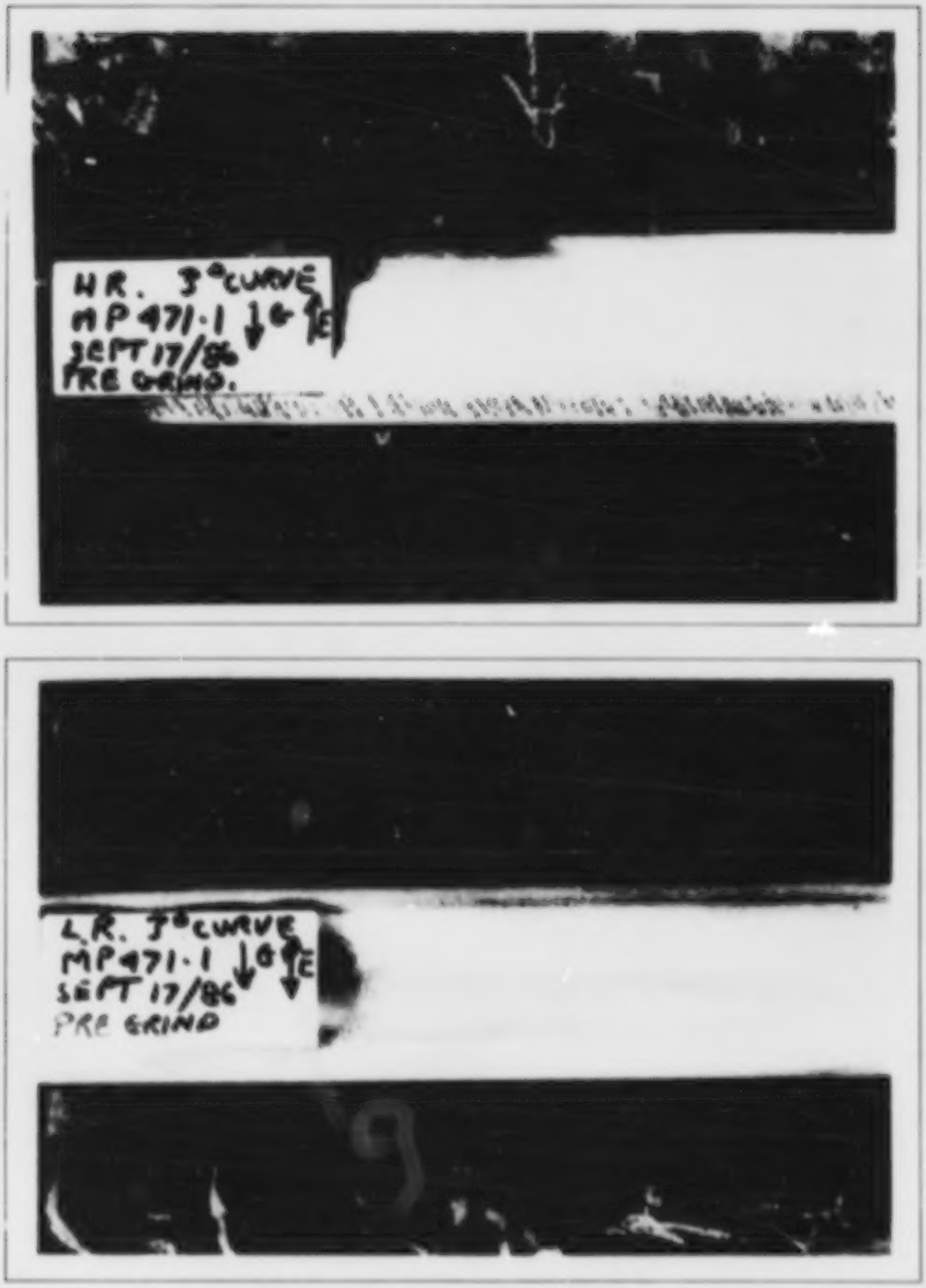

HR. 3° CURVE
MP 471.1 ↓G ↑E
SEPT 17/86
PRE GRIND.
LR. 3° CURVE
MP 471.1 ↓G ↓E
SEPT 17/86
PRE GRIND

Figure D.15: Surface condition of the high and low rails at BCR Test Site 3 before September 1986 test grinding

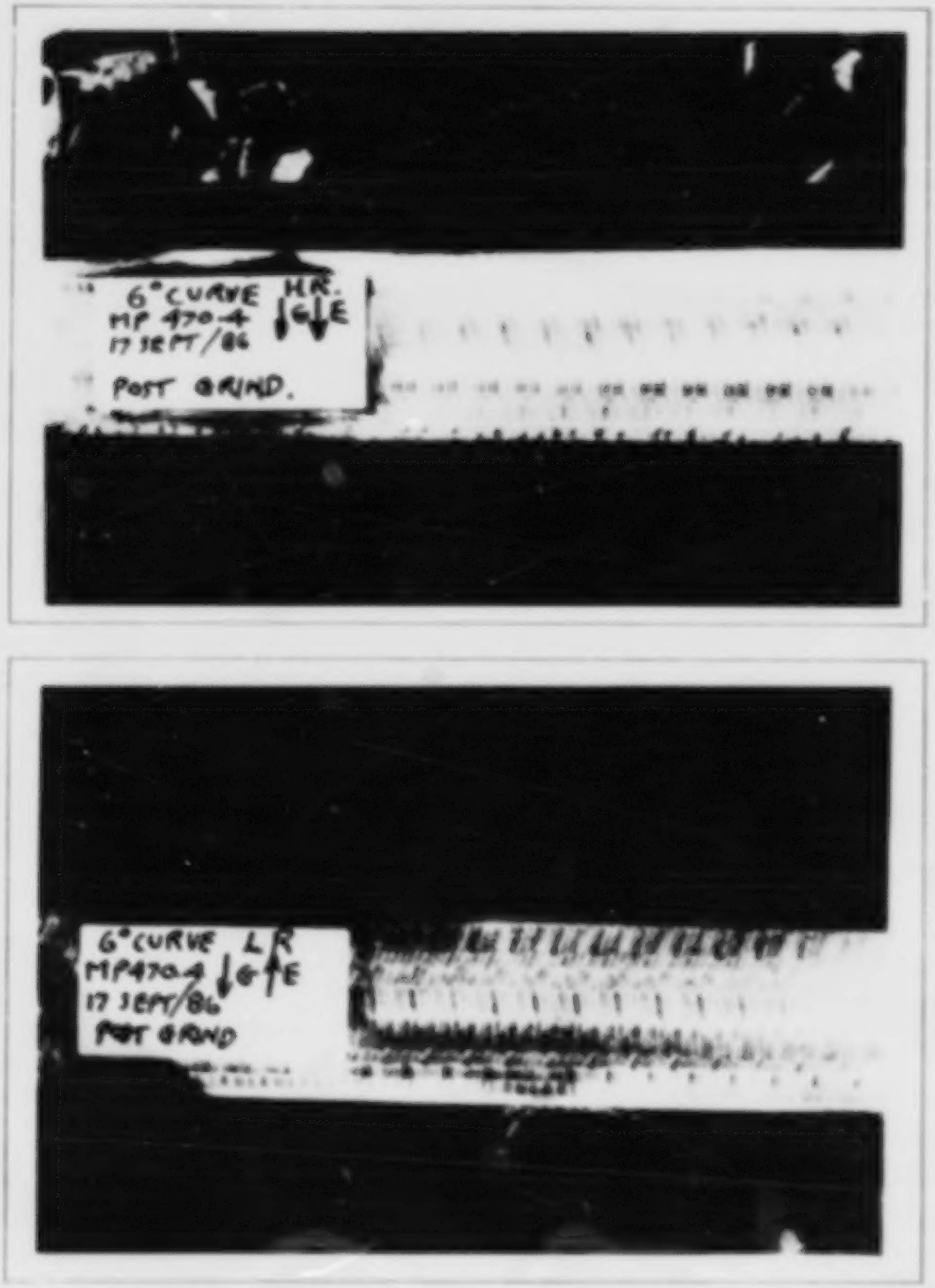

6°CURVE H.R.
MP 470.4
G E
17 SEPT/86
POST GRIND.
6°CURVE LR
MP470.4
G E
17 SEPT/86
POST GRIND

Figure D.16: Surface condition of the high and low rails at BCR Test Site 1 after September 1986 test grinding

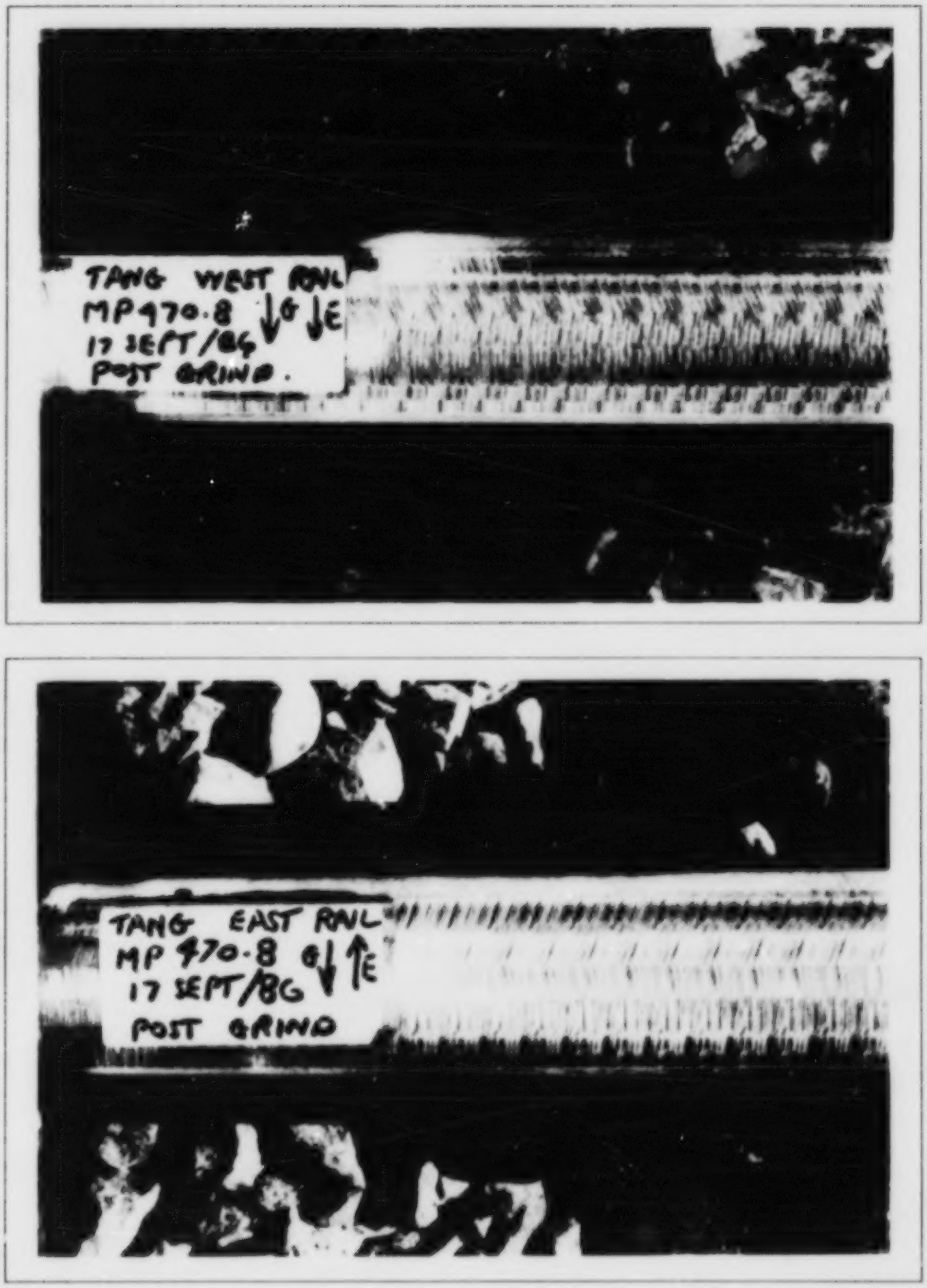

TANG WEST RAIL
MP 470.8 ↓G ↓E
17 SEPT/86
POST GRIND.
TANG EAST RAIL
MP 470.8 G↓ ↑E
17 SEPT/86
POST GRIND

Figure D.17: Surface condition of the west and east rails at BCR Test Site 2 after September 1986 test grinding

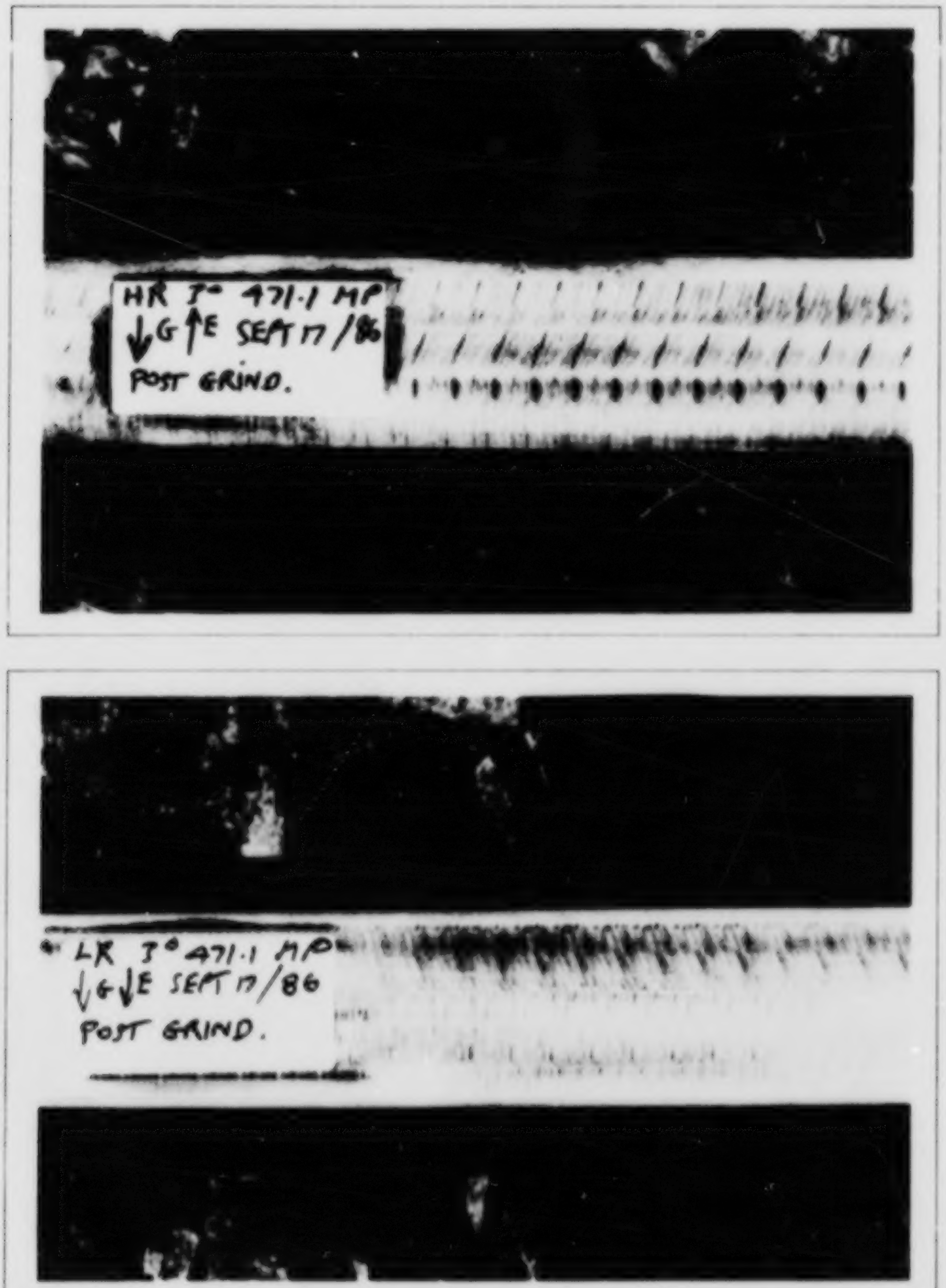

HR 3° 471.1 MP
↓G ↑E SEPT 17/86
POST GRIND.
LR 3° 471.1 MP
↓G ↓E SEPT 17/86
POST GRIND.

Figure D.18: Surface condition of the high and low rails at BCR Test Site 3 after September 1986 test grinding

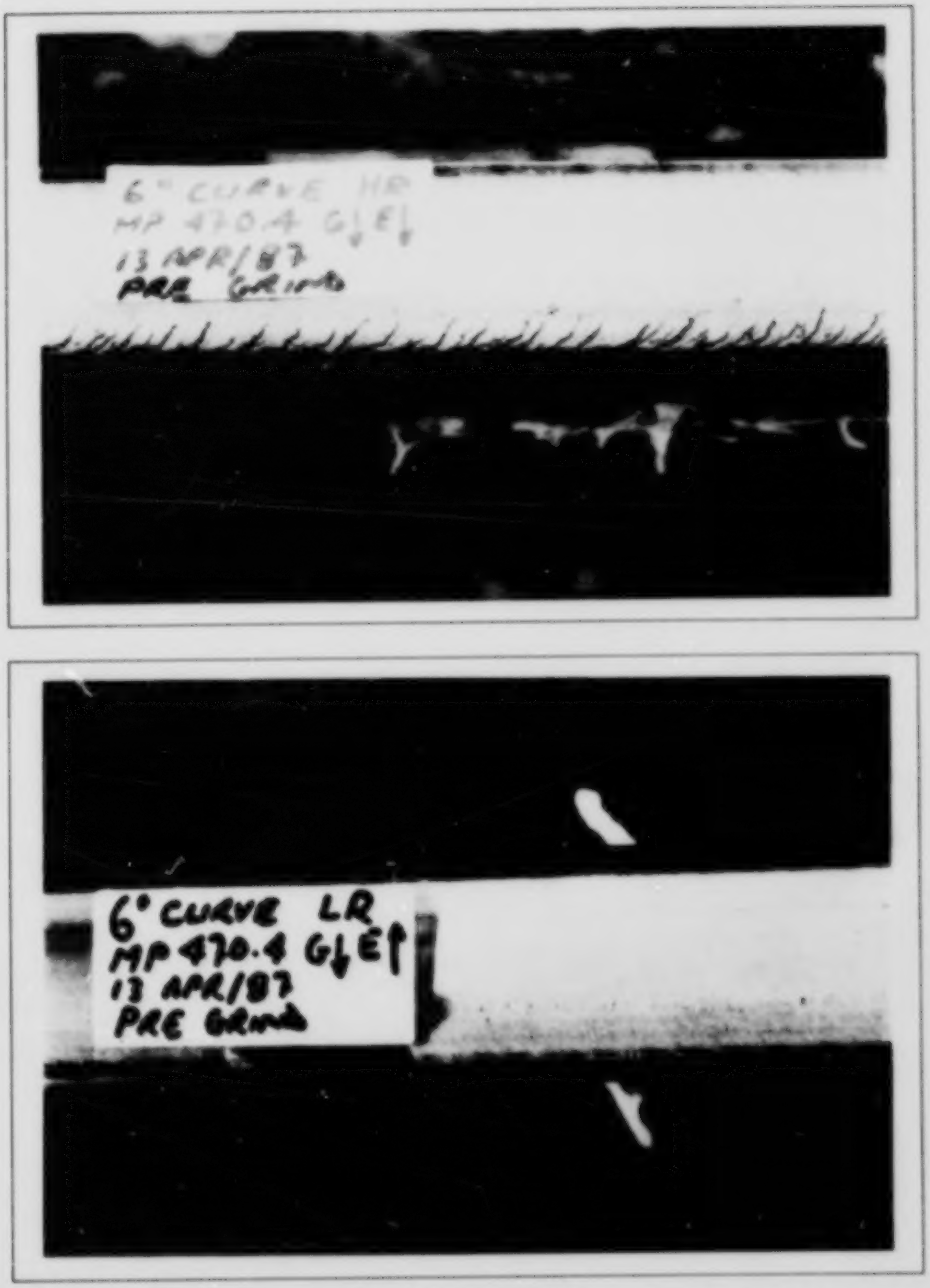

6° CURVE HR
MP 470.4 G↓E↓
13 APR/87
PRE GRIND
6° CURVE LR
MP 470.4 G↓E↑
13 APR/87
PRE GRIND

Figure D.19: Surface condition of the high and low rails at BCR Test Site 1 before April 1987 test grinding

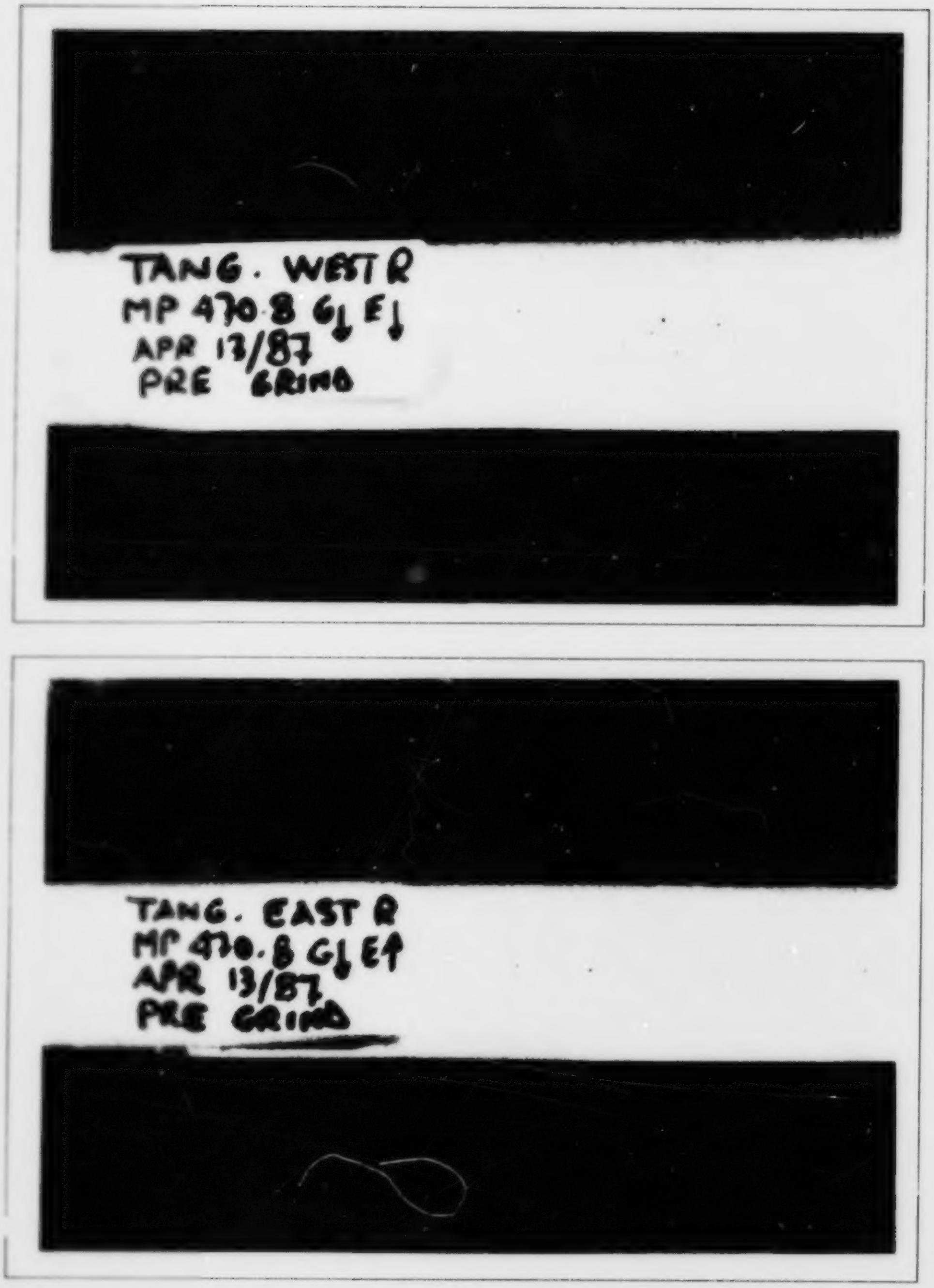

TANG. WEST R
MP 470.8 G↓ E↓
APR 13/87
PRE GRIND
TANG. EAST R
MP 470.8 G↓ E↑
APR 13/87
PRE GRIND

Figure D.20: Surface condition of the west and east rails at BCR Test Site 2 before April 1987 test grinding

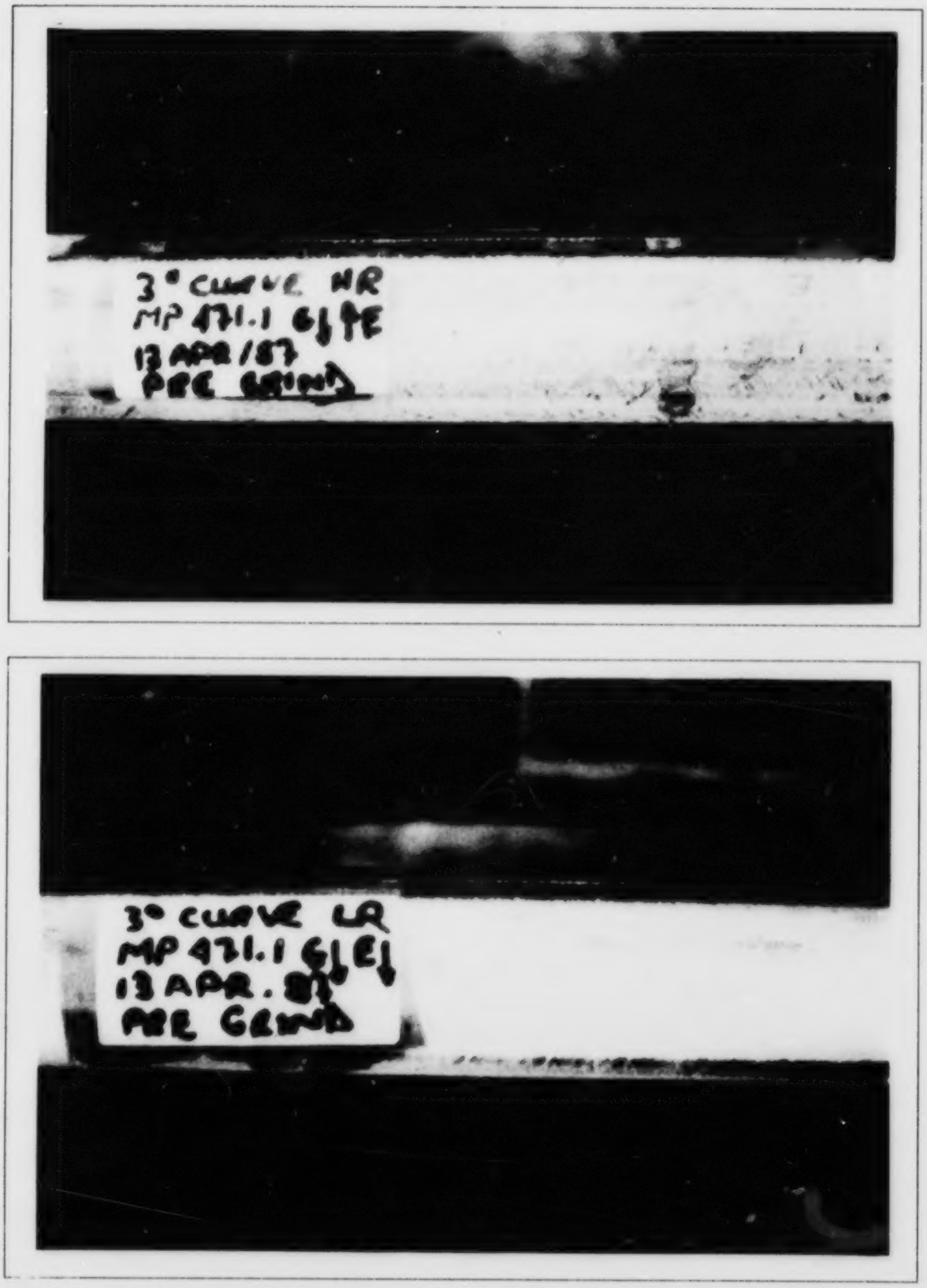

3° CURVE HR
MP 471.1 G½ TE
13 APR/87
PRE GRIND
3° CURVE LR
MP 471.1 G½ E½
13 APR. 87
PRE GRIND

Figure D.21: Surface condition of the high and low rails at BCR Test Site 3 before April 1987 test grinding

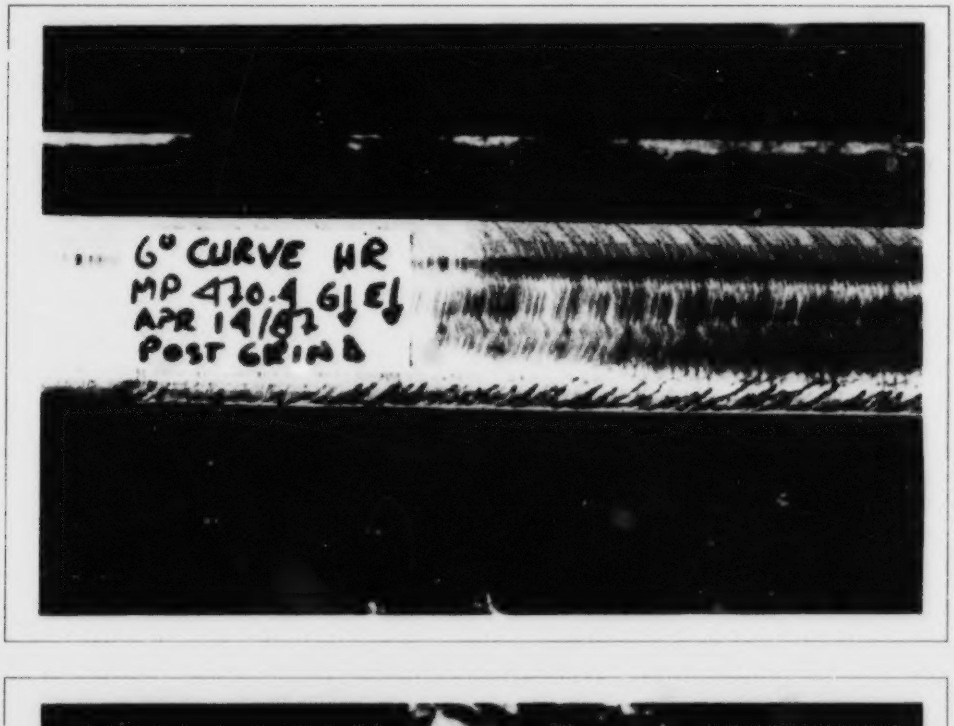

6° CURVE HR
MP 470.4 G↓ E↓
APR 14/87
POST GRIND
6° CURVE LR
MP 470.4 G↓ E↑
APR 14/87
POST GRIND

Figure D.22: Surface condition of the high and low rails at BCR Test Site 1 after April 1987 test grinding

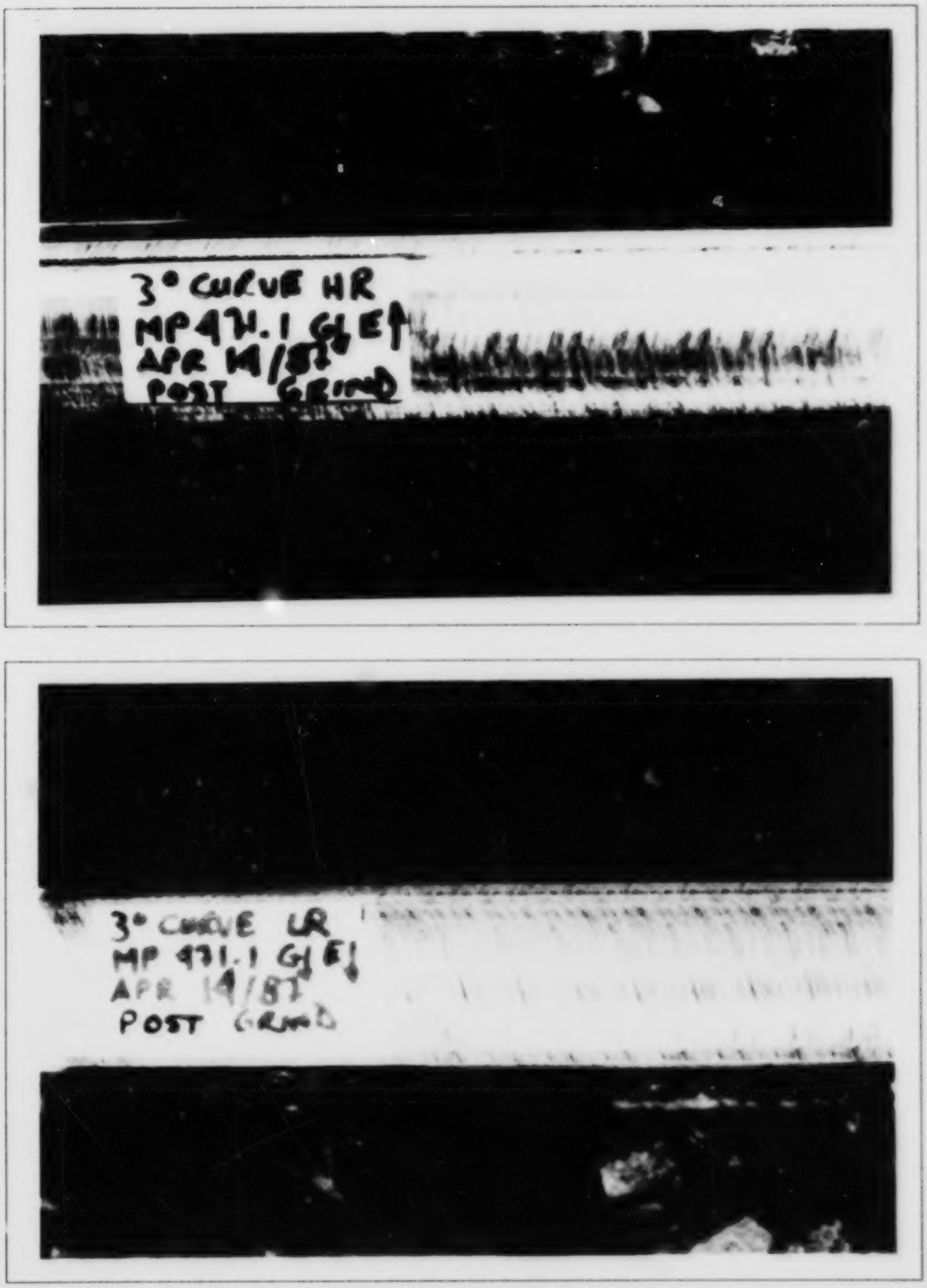

3° CURVE HR
MP 471.1 GLE↑
APR 14/87
POST GRIND
3° CURVE LR
MP 471.1 GLE↓
APR 14/87
POST GRIND

Figure D.23: Surface condition of the high and low rails at BCR Test Site 3 after April 1987 test grinding

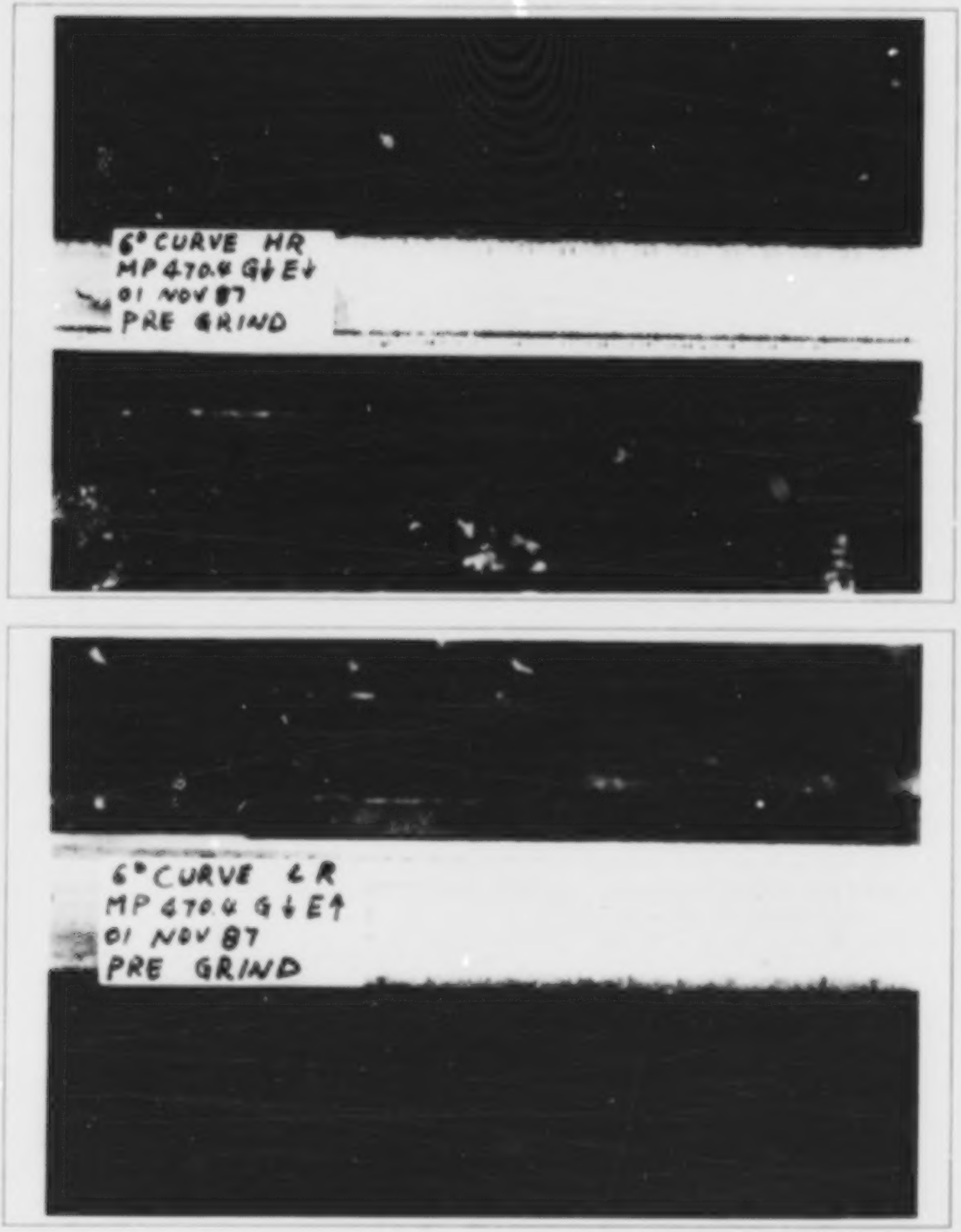

6° CURVE HR
MP 470.4 G↓ E↓
01 NOV 87
PRE GRIND
6° CURVE LR
MP 470.4 G↓ E↑
01 NOV 87
PRE GRIND

Figure D.24: Surface condition of the high and low rails at BCR Test Site 1 before November 1987 test grinding

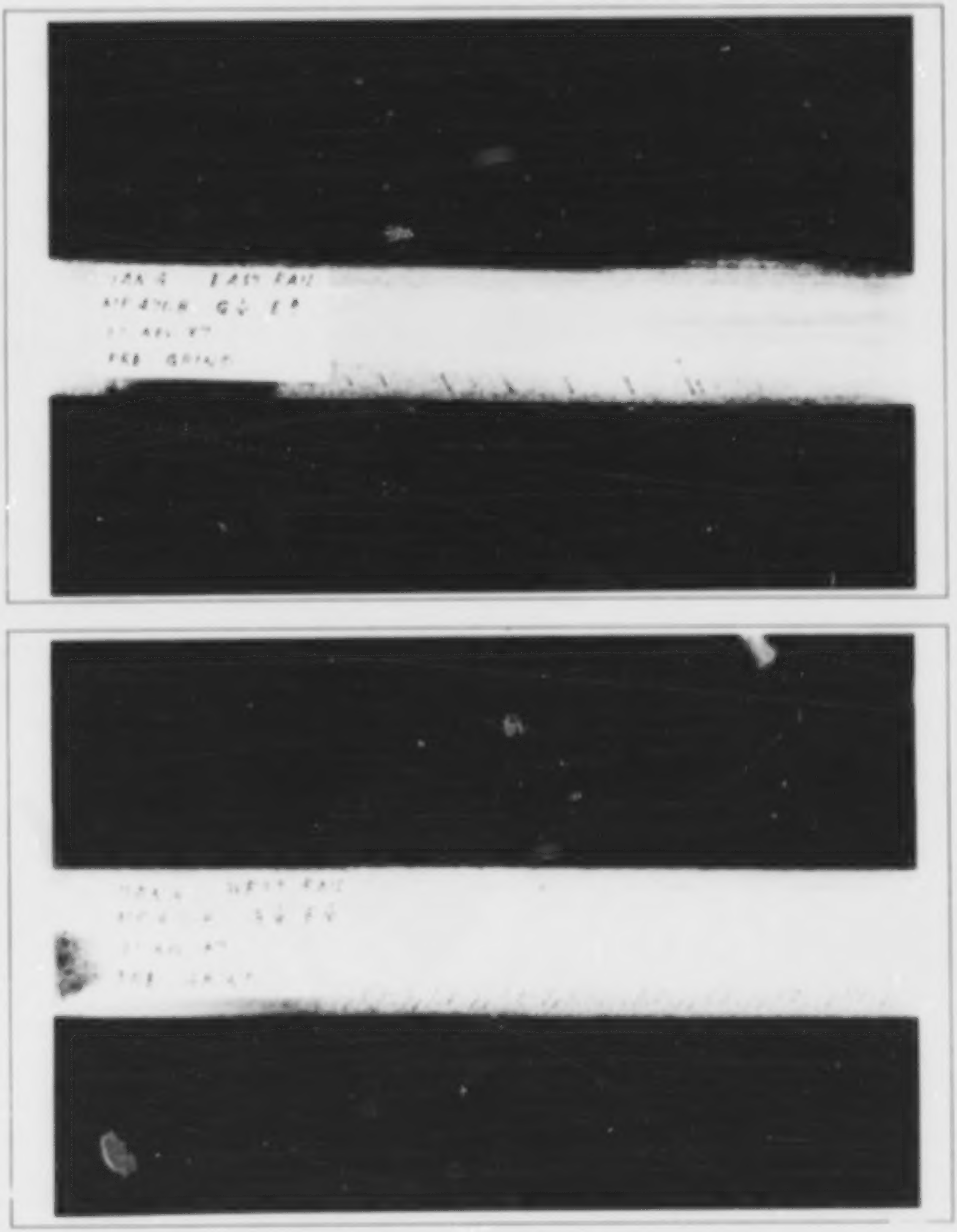

EAST RAIL
PRE GRIND
WEST RAIL

Figure D.25: Surface condition of the high and low rails at BCR Test Site 2 before November 1987 test grinding

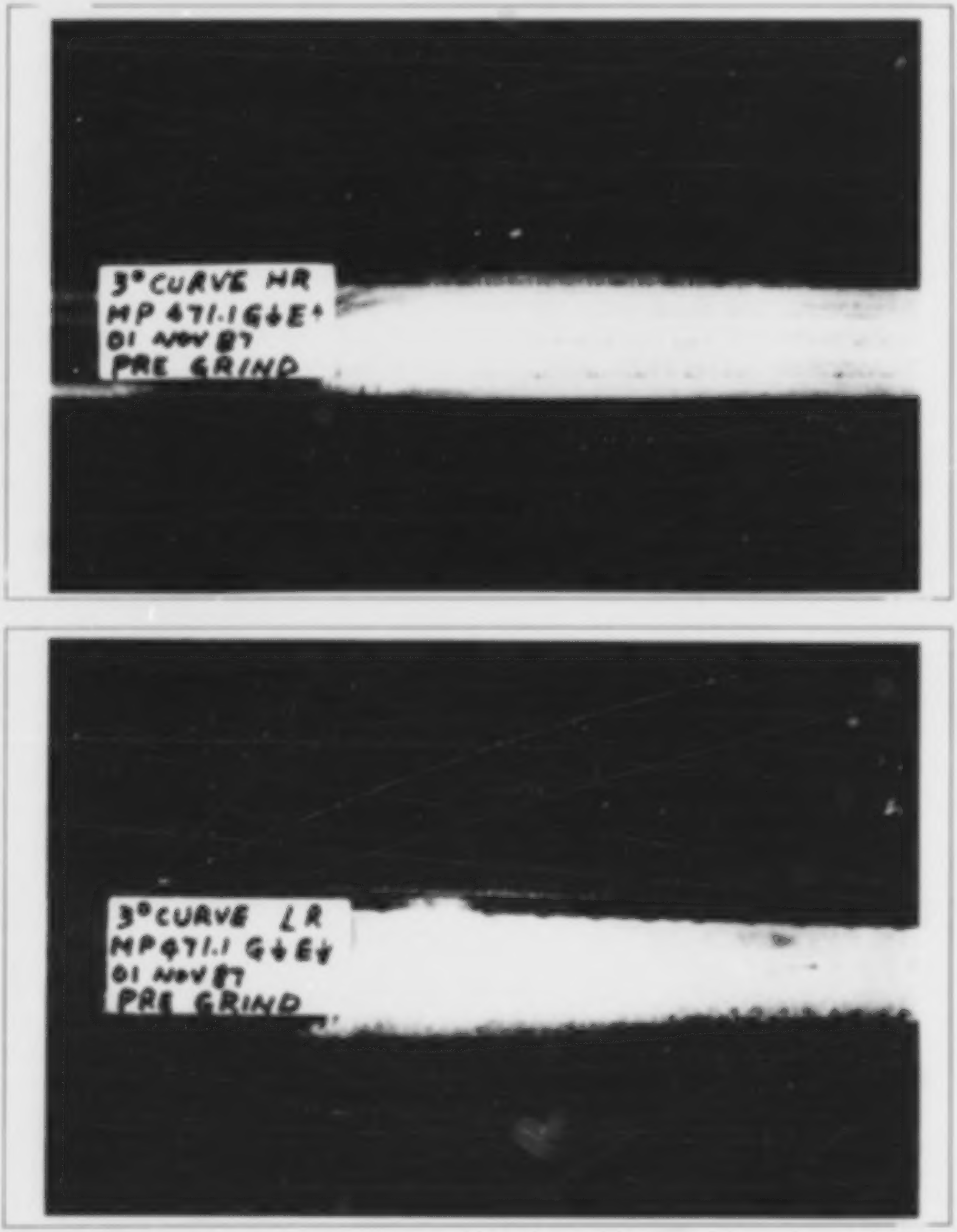

3° CURVE HR
MP 471.1G↓E↑
01 NOV 87
PRE GRIND
3° CURVE LR
MP471.1 G↓E↓
01 NOV 87
PRE GRIND

Figure D.26: Surface condition of the high and low rails at BCR Test Site 3 before November 1987 test grinding

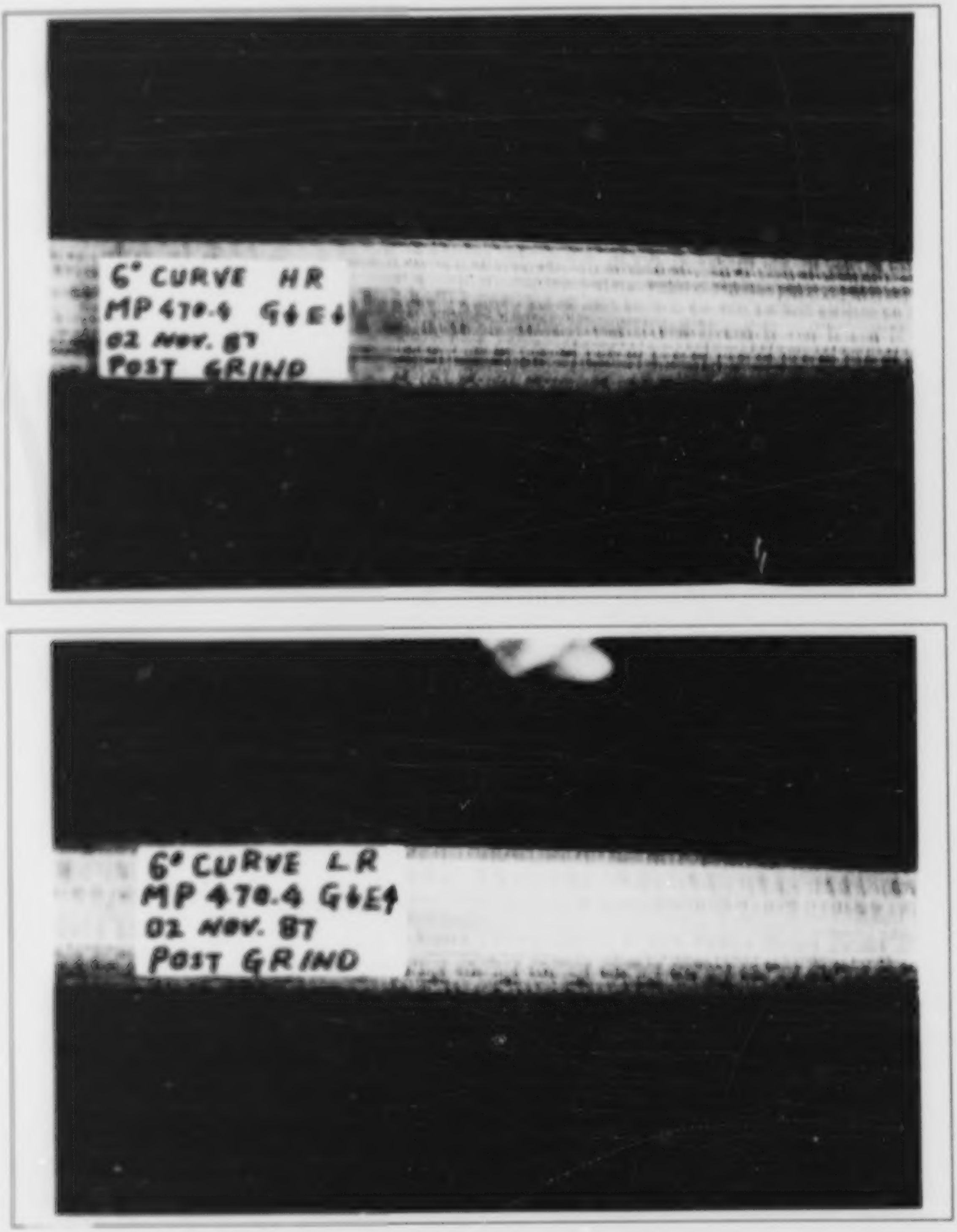

6° CURVE HR
MP 470.4 G&E↑
02 NOV. 87
POST GRIND
6° CURVE LR
MP 470.4 G&E↑
02 NOV. 87
POST GRIND

Figure D.27: Surface condition of the high and low rails at BCR Test Site 1 after November 1987 test grinding

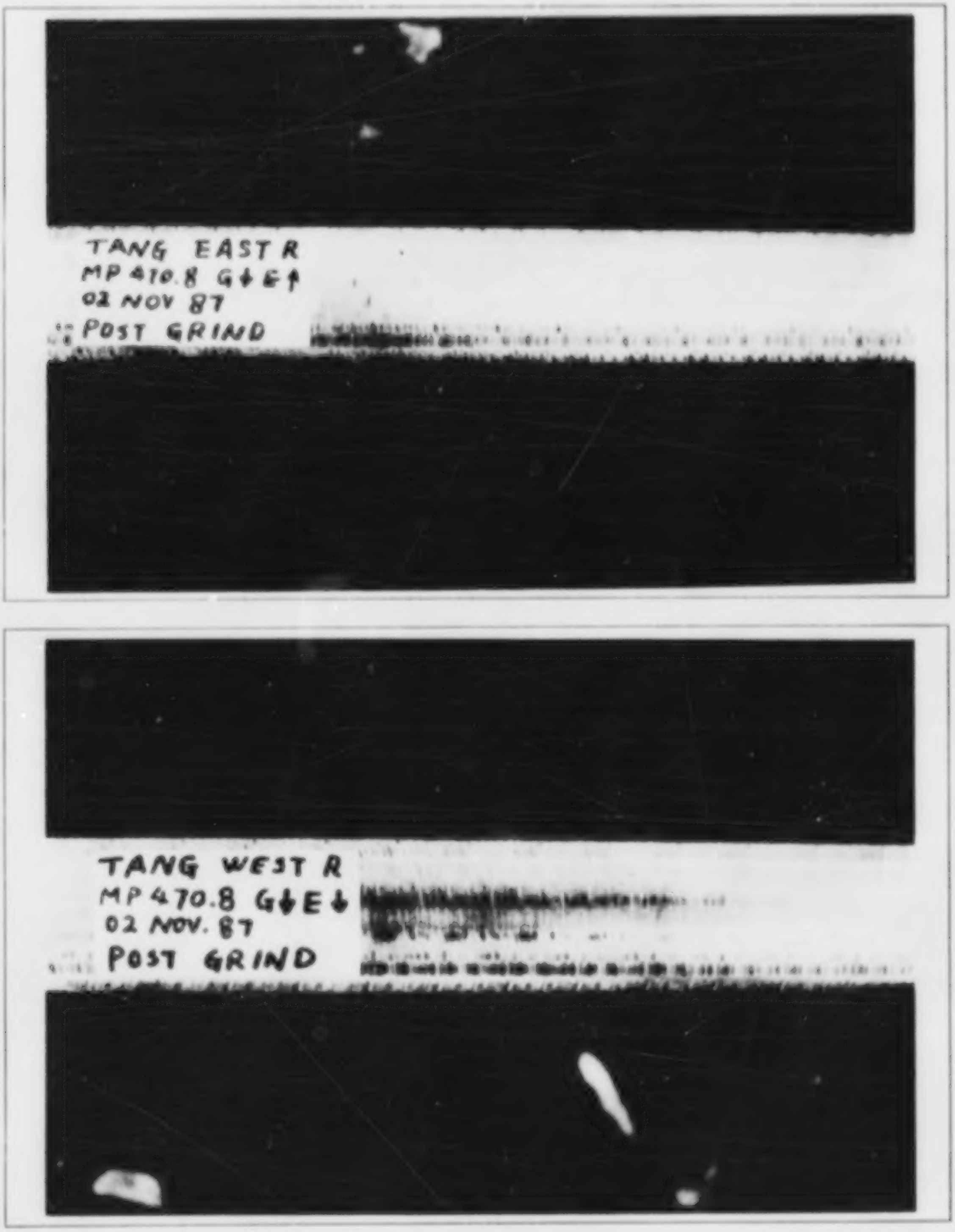

TANG EAST R
MP 470.8 G↓E↑
02 NOV 87
POST GRIND
TANG WEST R
MP 470.8 G↓E↓
02 NOV. 87
POST GRIND

Figure D.28: Surface condition of the high and low rails at BCR Test Site 2 after November 1987 test grinding

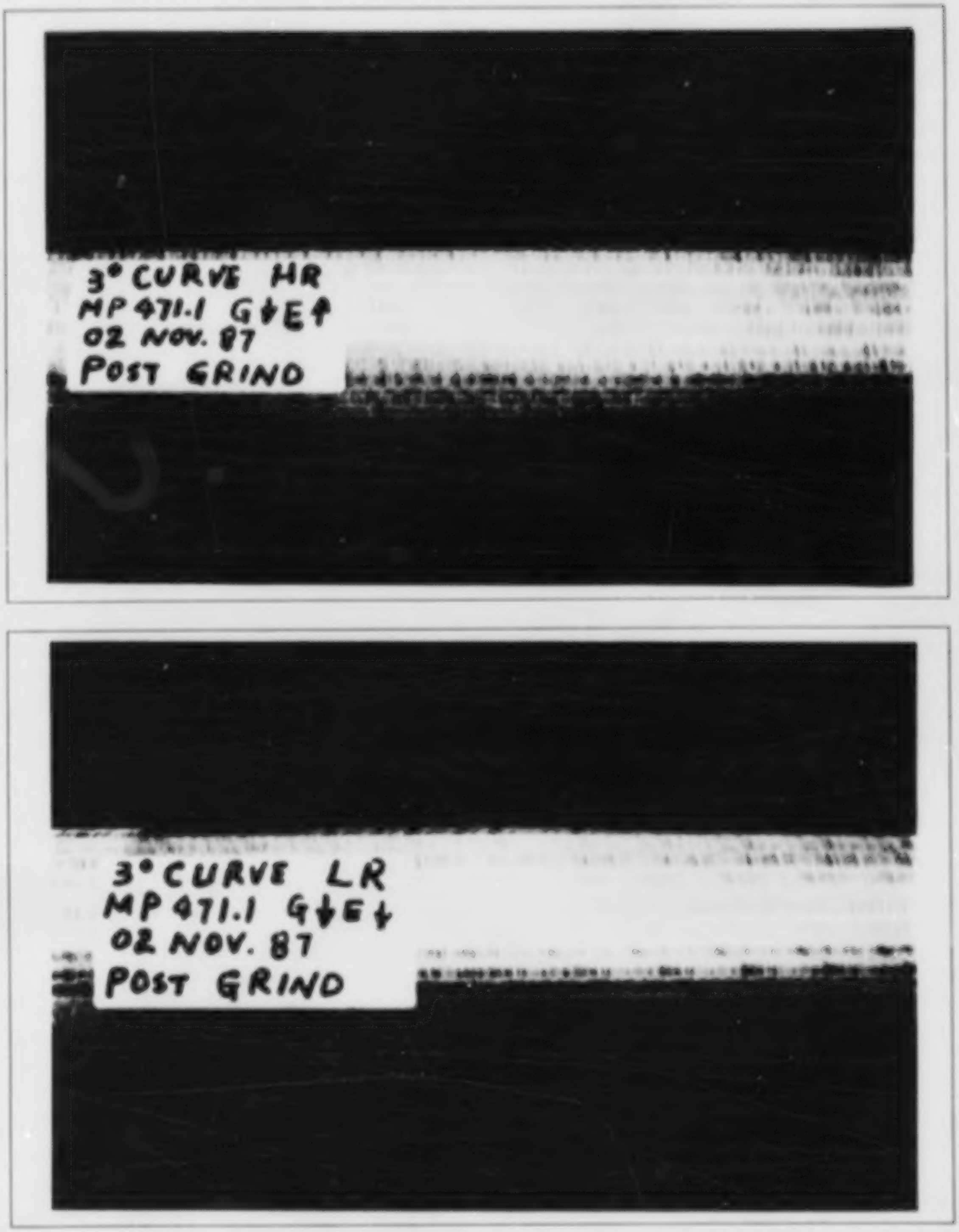

3° CURVE HR
MP 471.1 G↓E↑
02 NOV. 87
POST GRIND
3° CURVE LR
MP 471.1 G↓E↓
02 NOV. 87
POST GRIND

Figure D.29: Surface condition of the high and low rails at BCR Test Site 3 after November 1987 test grinding

APPENDIX E

PREVENTIVE MAINTENANCE GRINDING DETAILS OF RAIL HEAD PROFILES

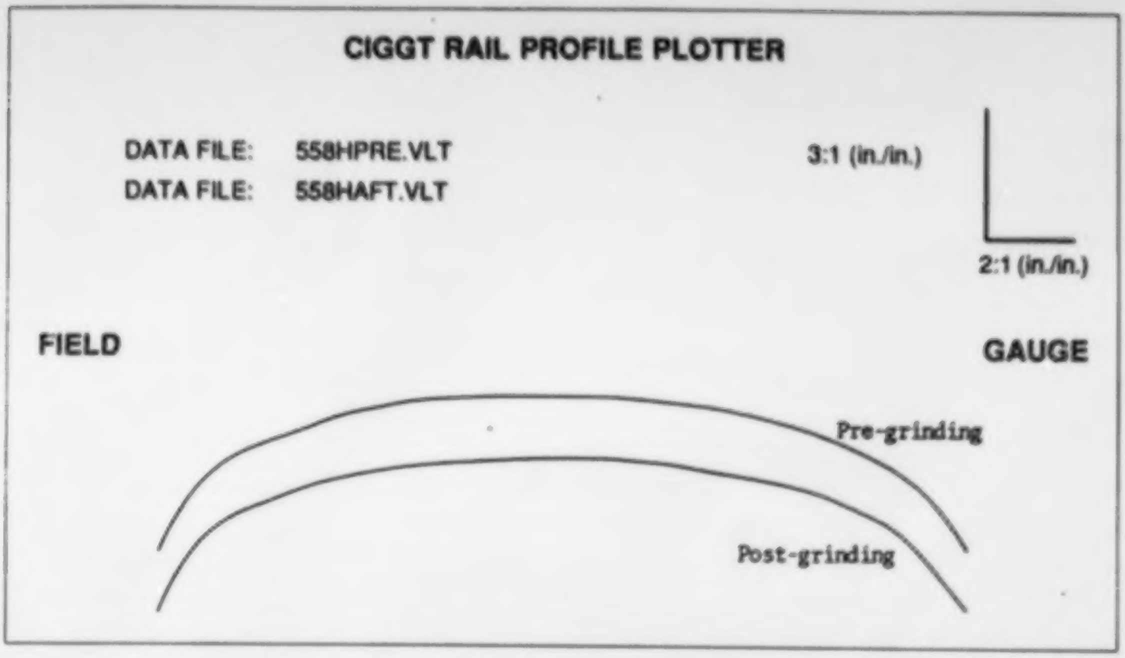


Figure E.1: Measured profiles of high rail at CPR Test Site 1 before and after September 1986 test grinding

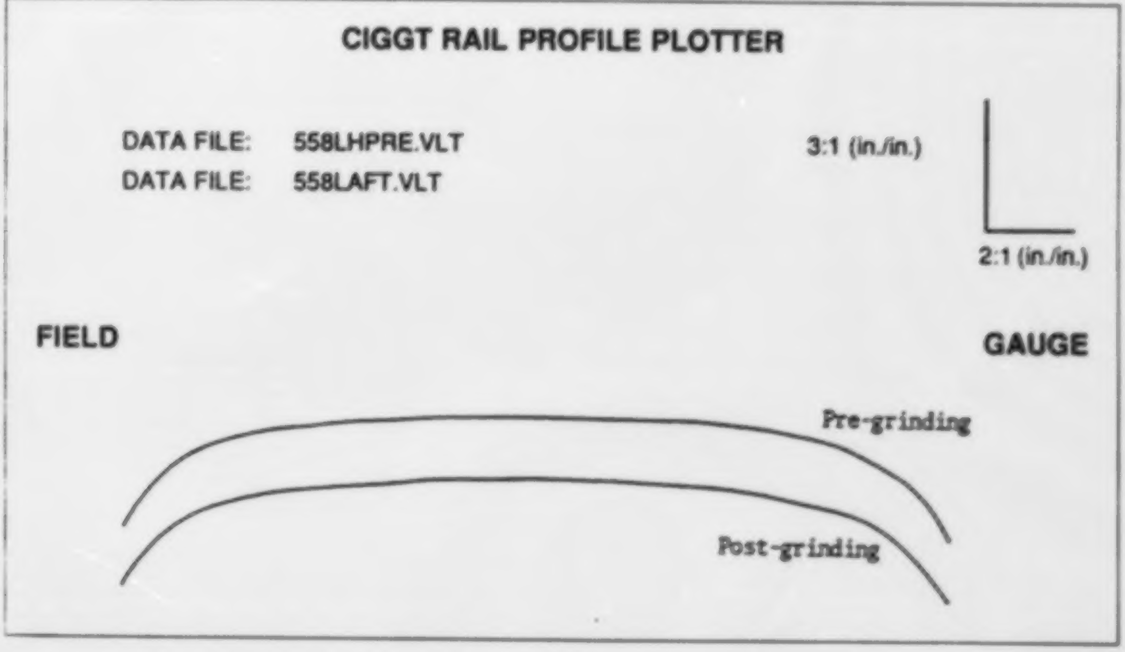


Figure E.2: Measured profiles of low rail at CPR Test Site 1 before and after September 1986 test grinding

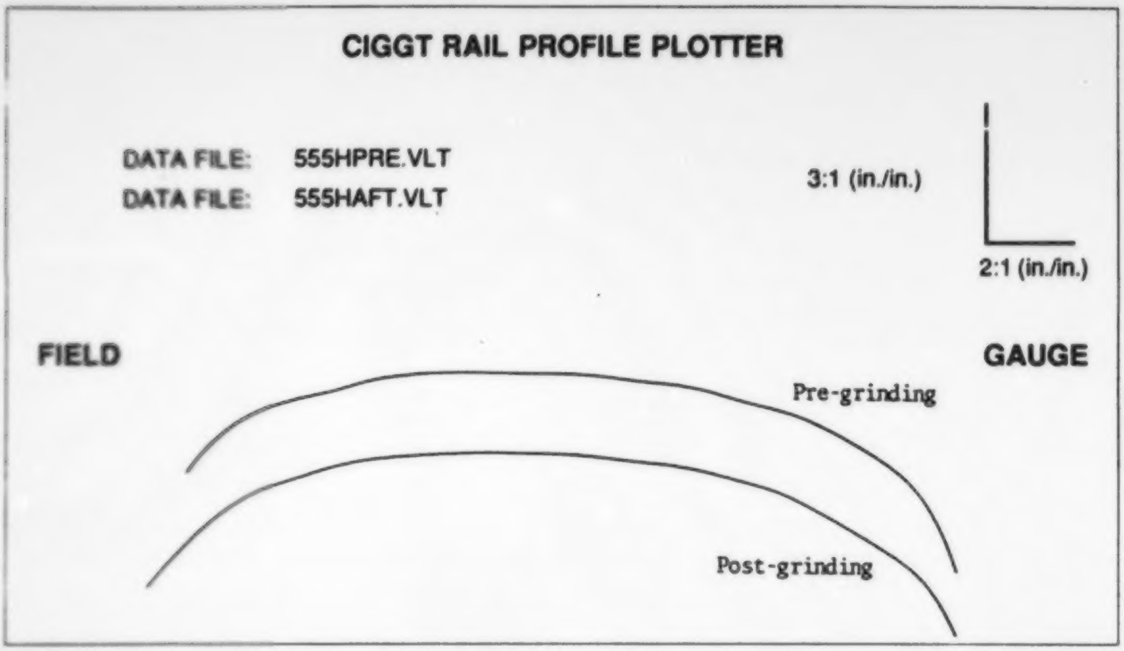


Figure E.3: Measured profiles of high rail at CPR Test Site 2 before and after September 1986 test grinding

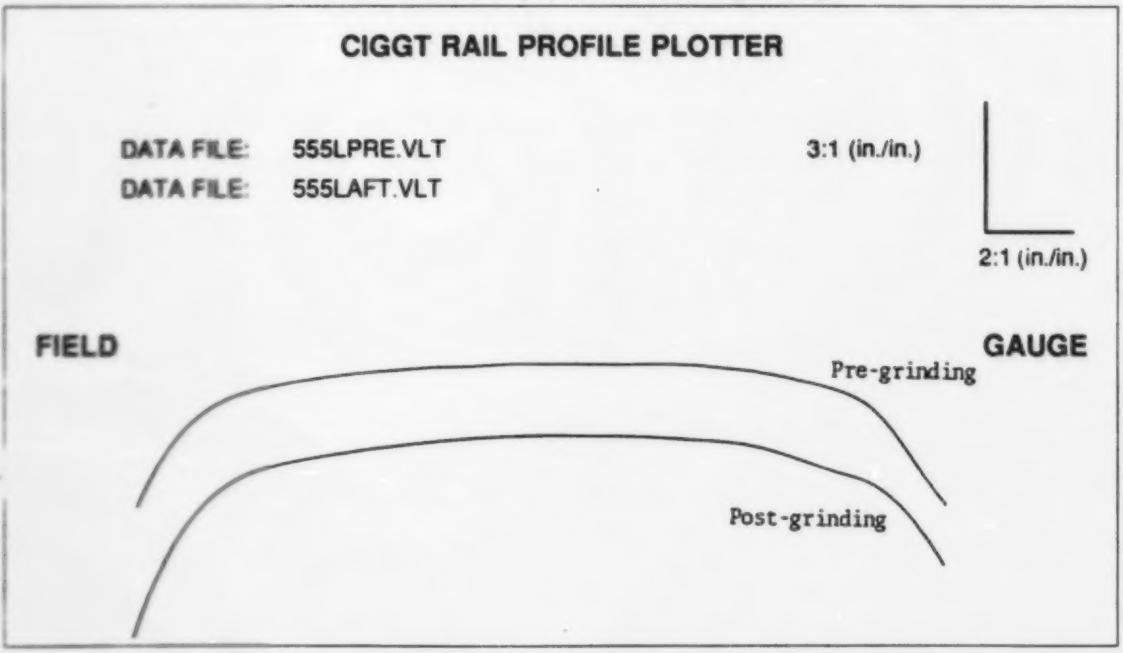


Figure E.4: Measured profiles of low rail at CPR Test Site 2 before and after September 1986 test grinding

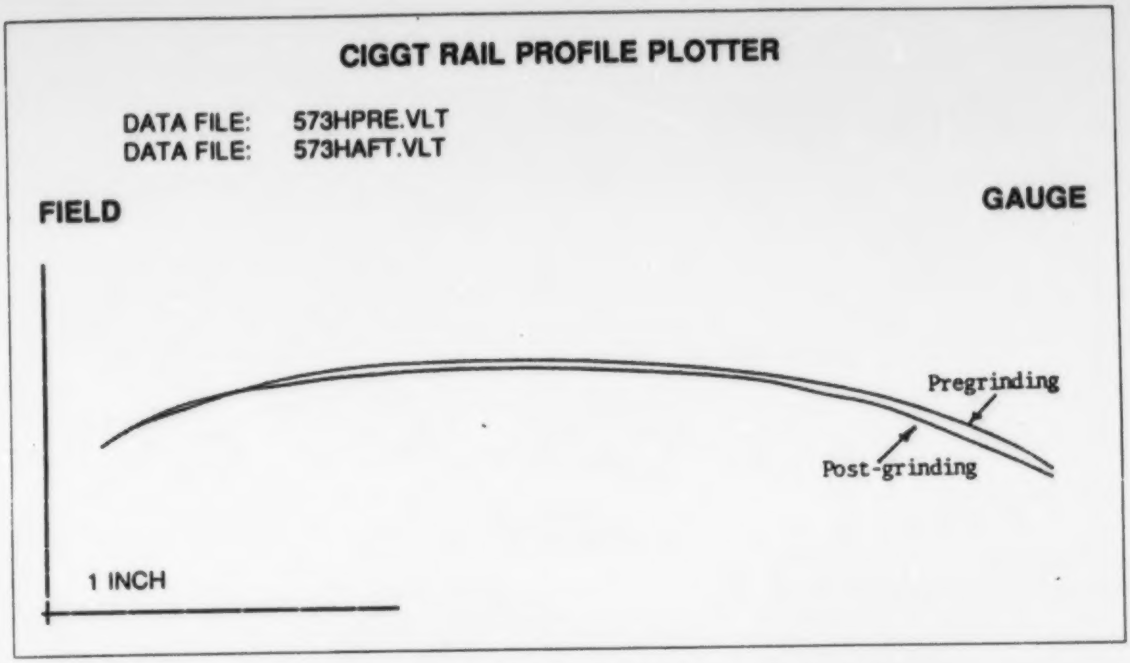


Figure E.5: Measured profiles of high rail at CPR Test Site 4 before and after August 1987 test grinding

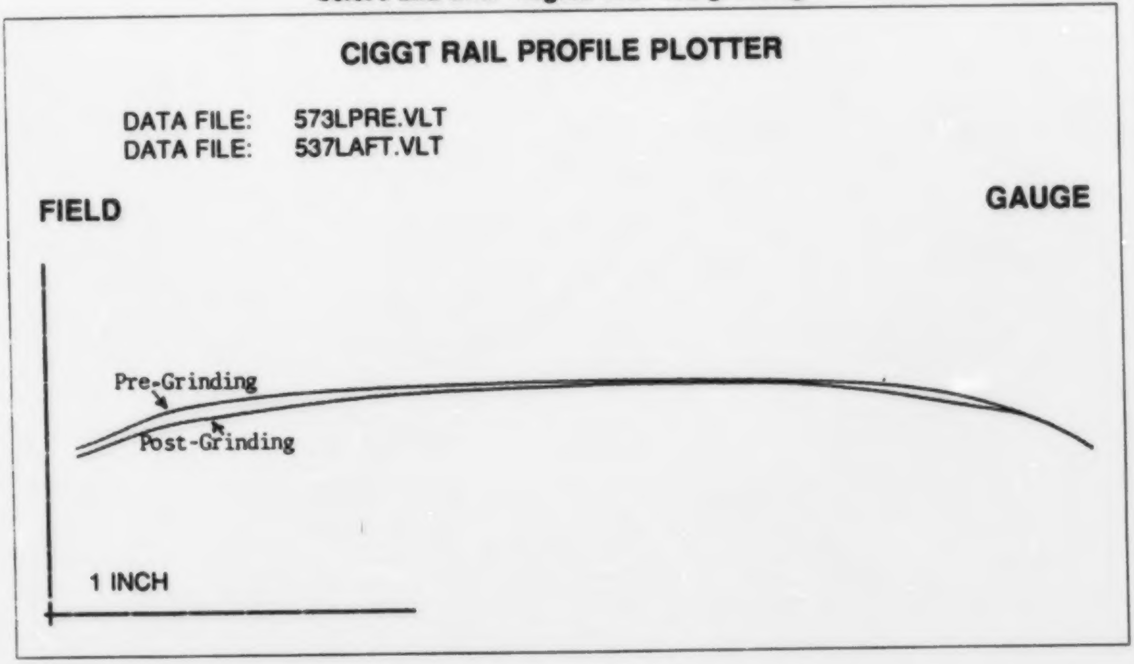


Figure E.6: Measured profiles of low rail at CPR Test Site 4 before and after August 1987 test grinding

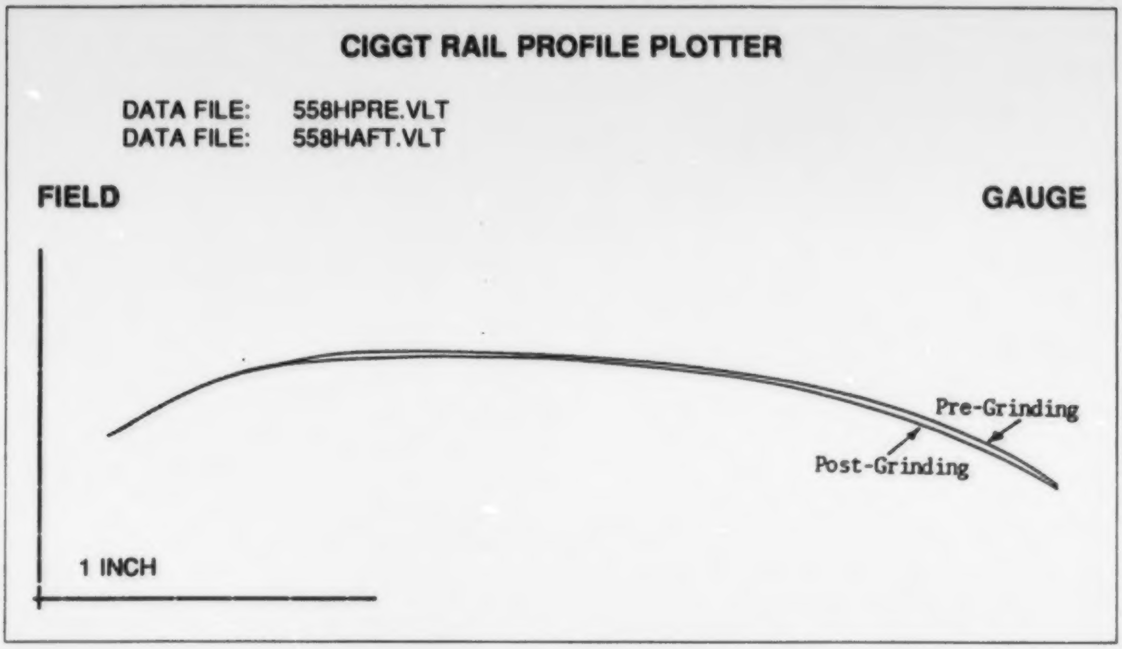


Figure E.7: Measured profiles of high rail at CPR Test Site 1 before and after August 1987 test grinding

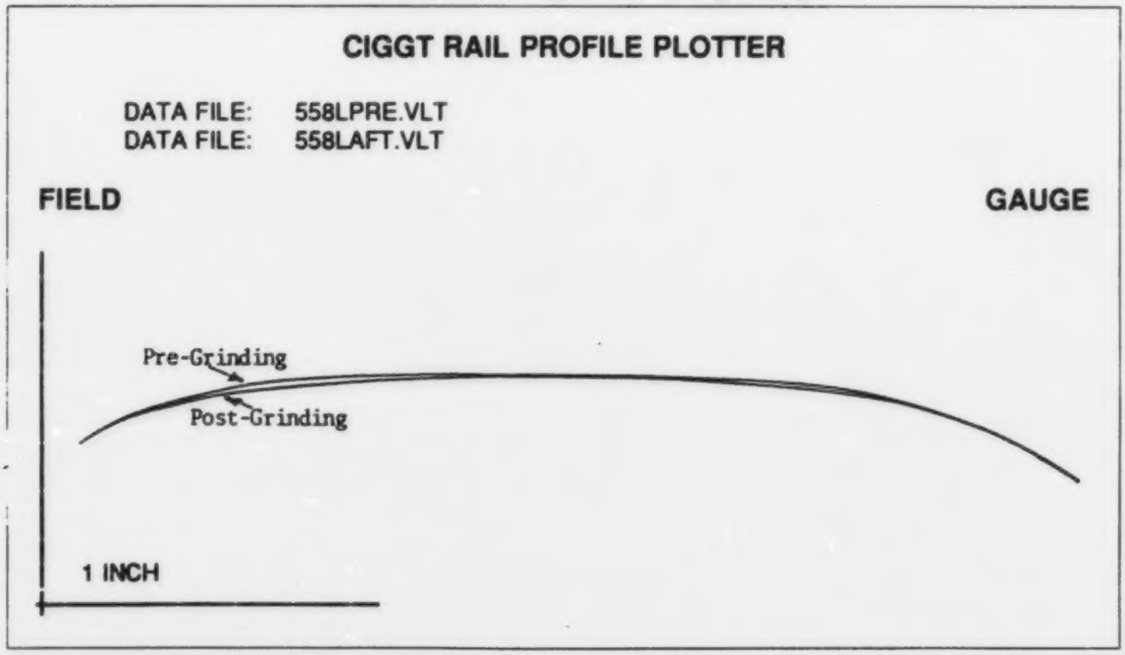


Figure E.8: Measured profiles of low rail at CPR Test Site 1 before and after August 1987 test grinding

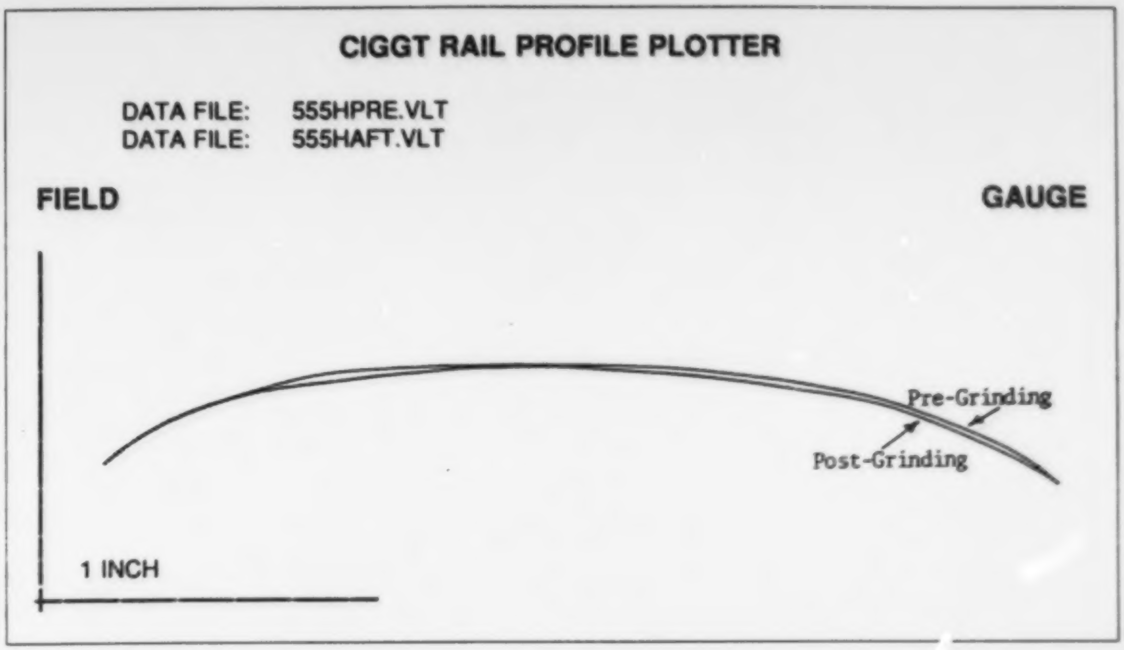


Figure E.9: Measured profiles of high rail at CPR Test Site 2 before and after August 1987 test grinding

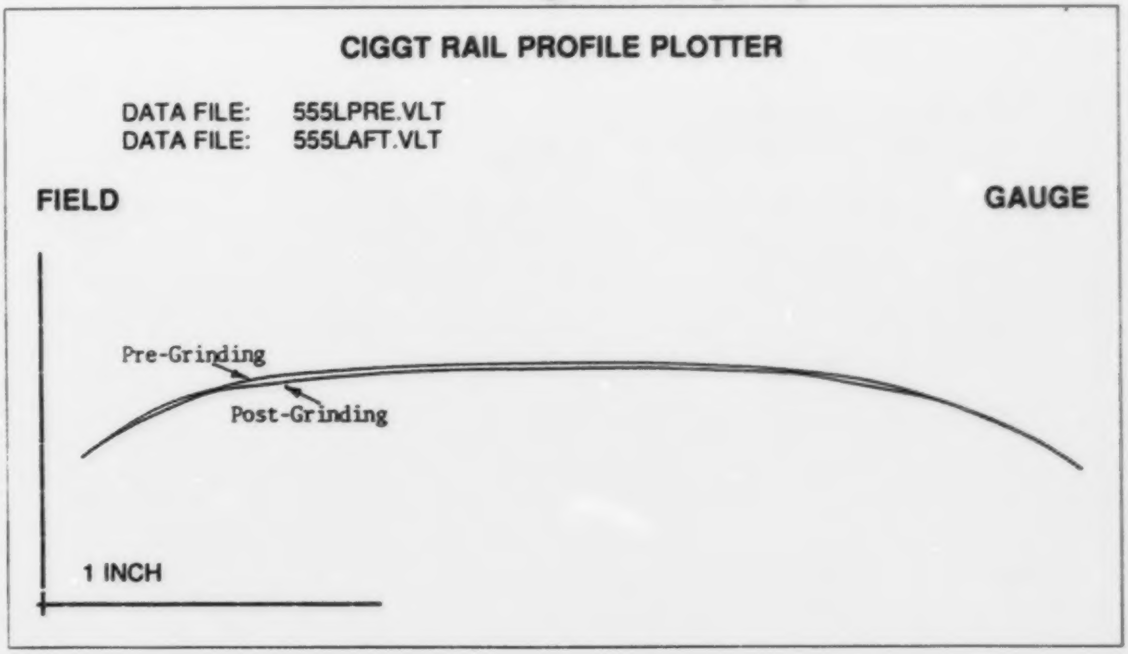


Figure E.10: Measured profiles of low rail at CPR Test Site 2 before and after August 1987 test grinding

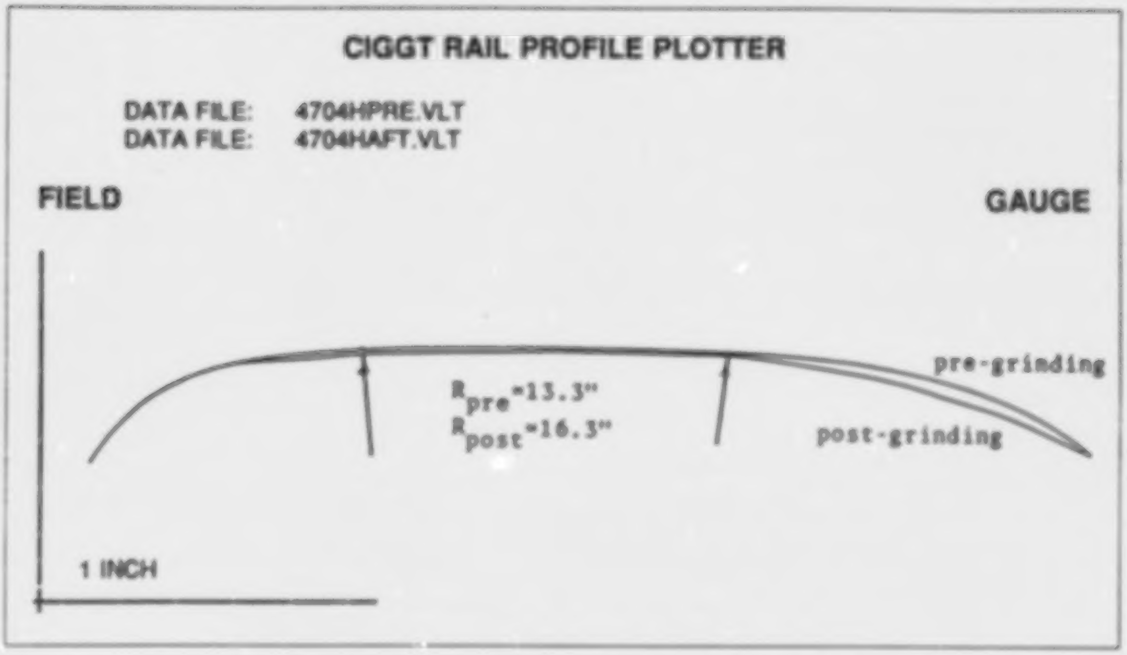


Figure E.11: Measured profiles of high rail at BCR Test Site 1 before and after September 1986 test grinding

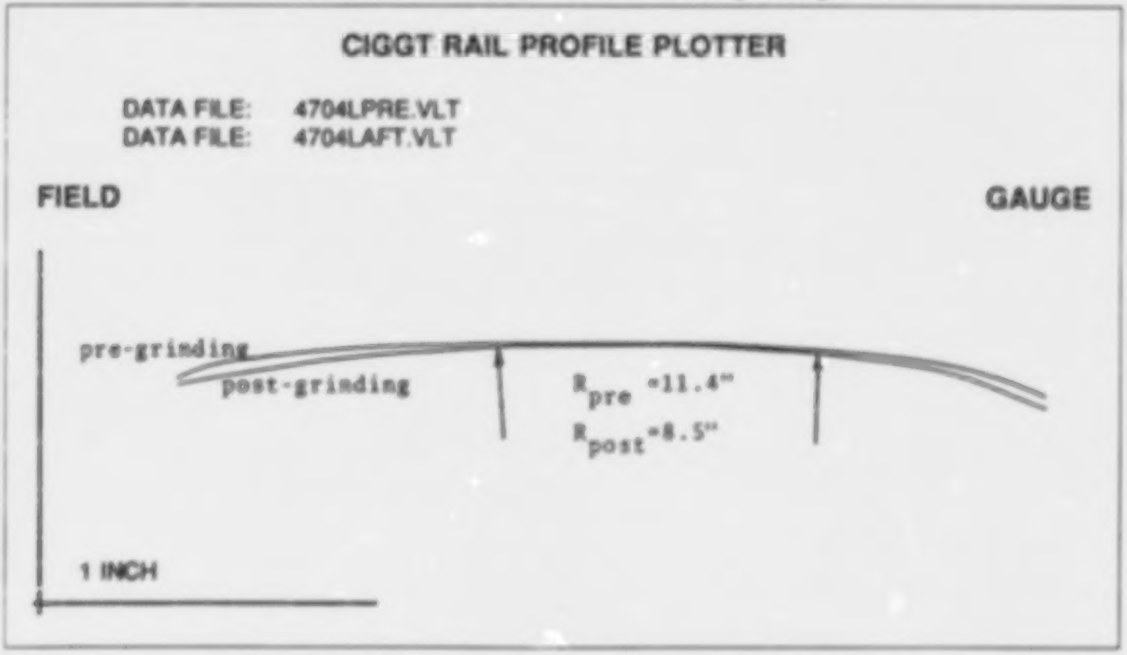


Figure E.12: Measured profiles of low rail at BCR Test Site 1 before and after September 1986 test grinding

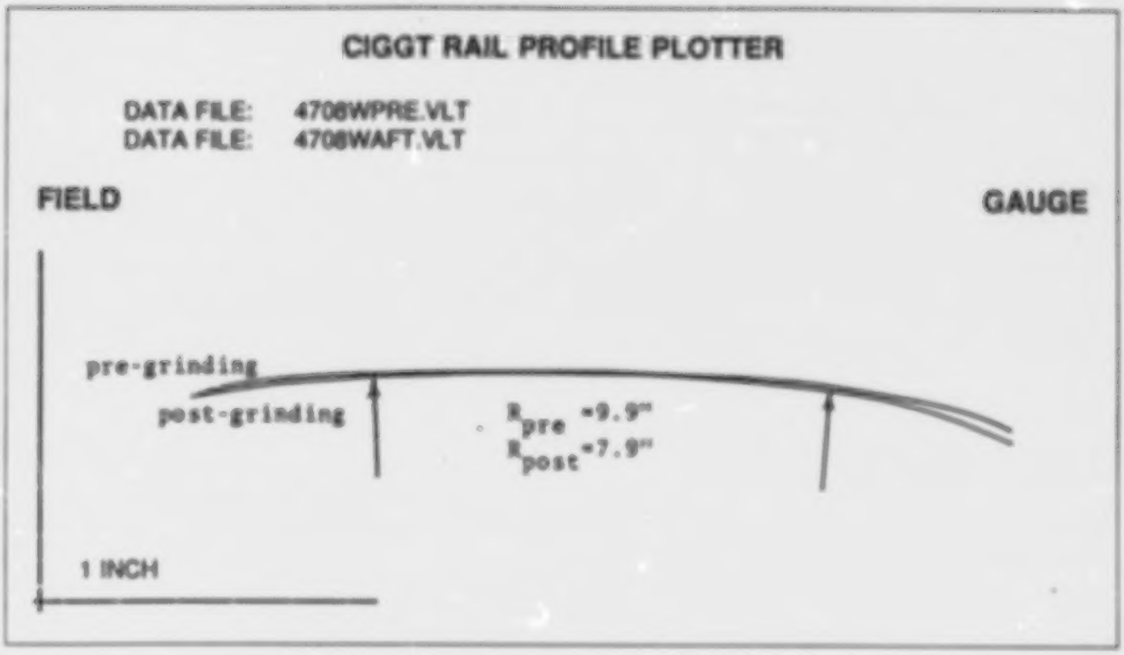


Figure E.13: Measured profiles of west rail at BCR Test Site 2 before and after September 1986 test grinding

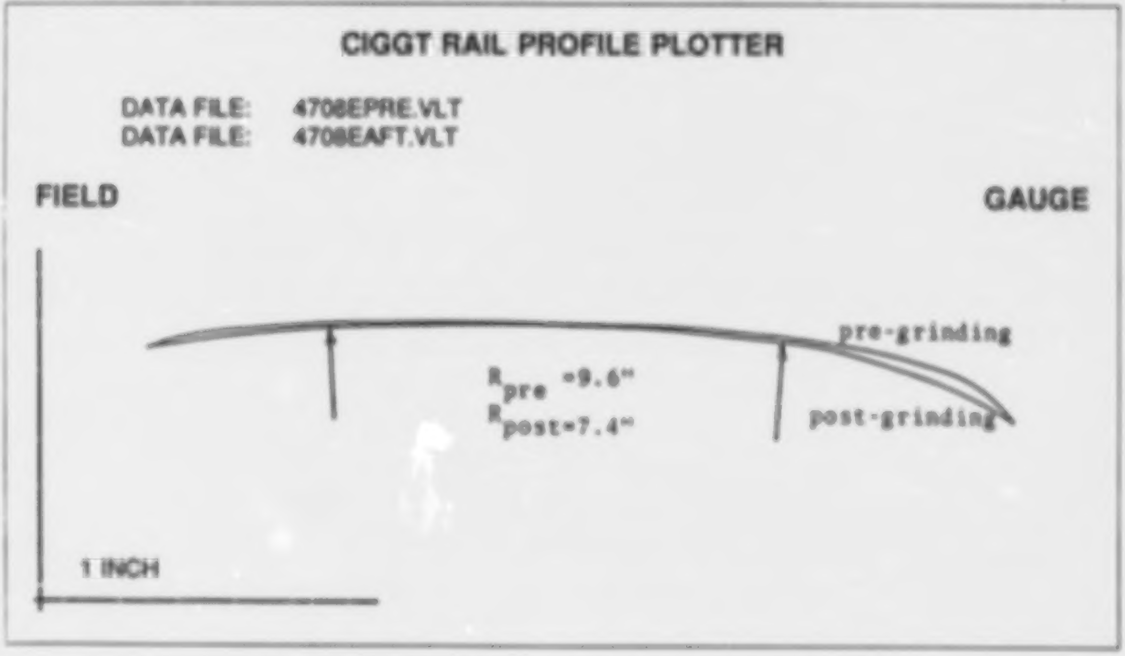


Figure E.14: Measured profiles of east rail at BCR Test Site 2 before and after September 1986 test grinding

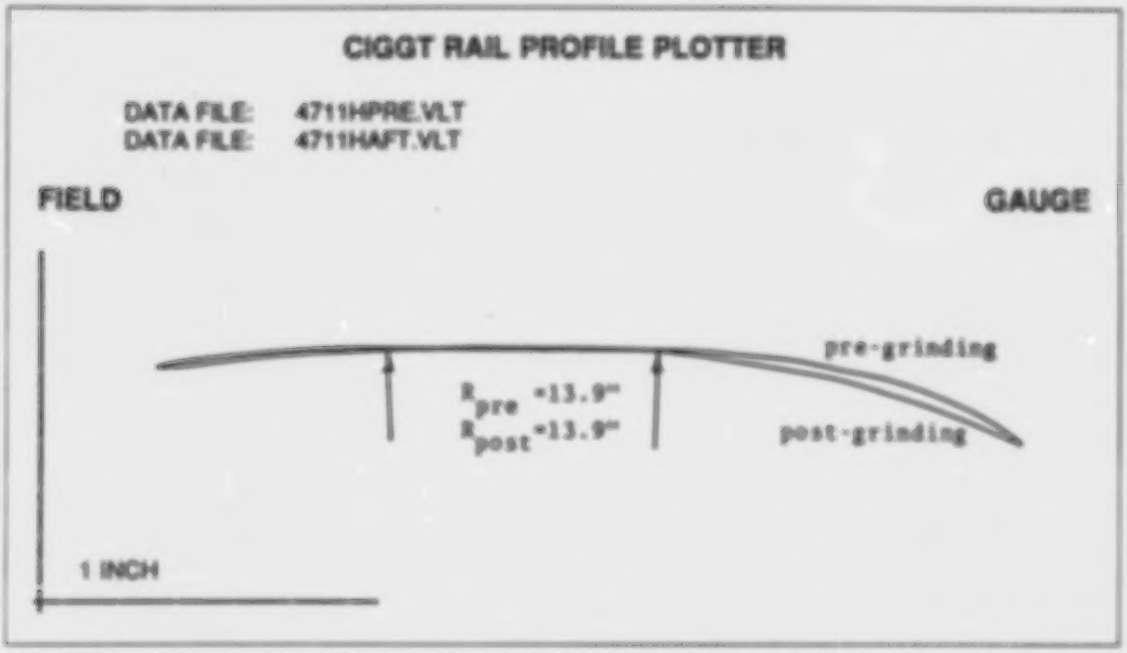


Figure E.15: Measured profiles of high rail at BCR Test Site 3 before and after September 1986 test grinding

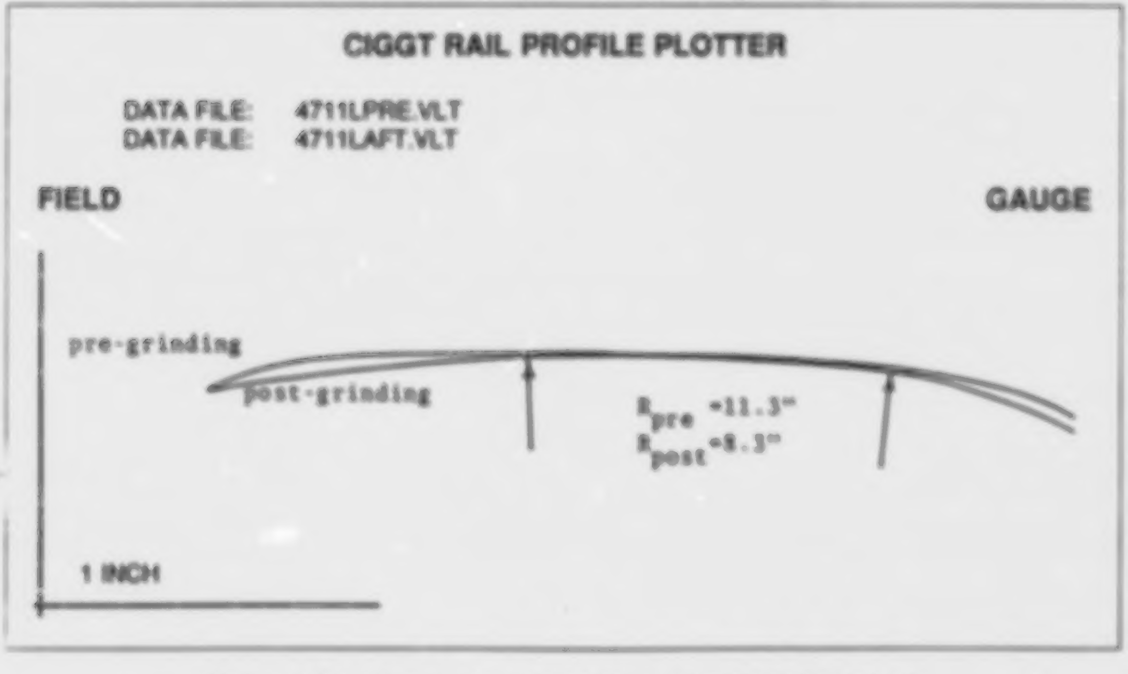


Figure E.16: Measured profiles of low rail at BCR Test Site 3 before and after September 1986 test grinding

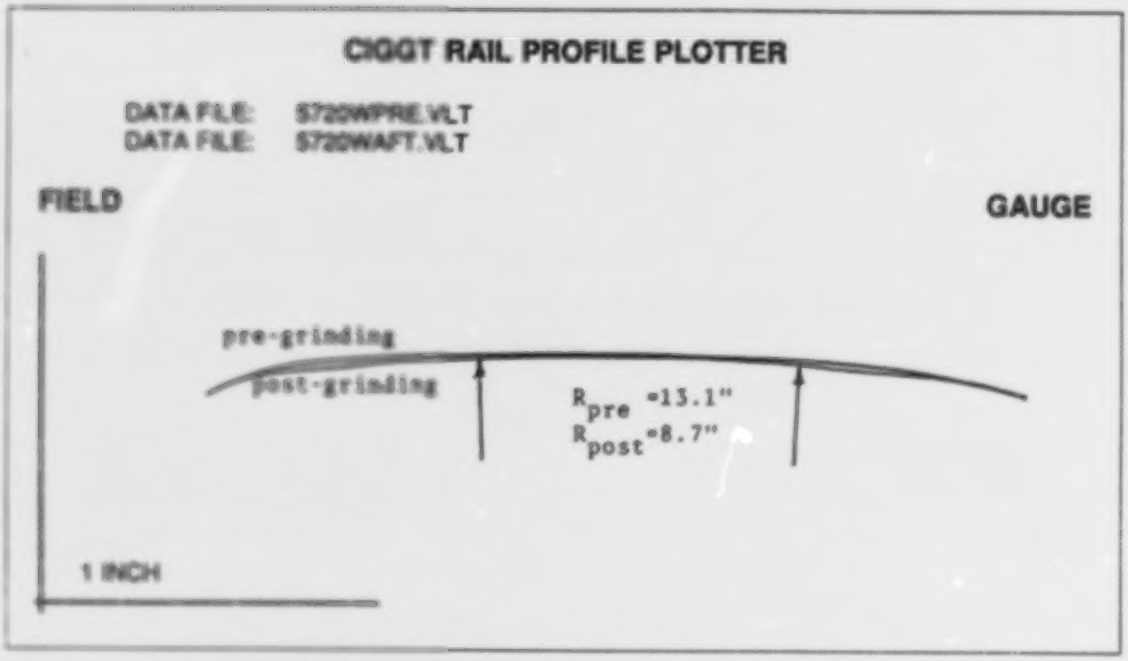


Figure E.17: Measured profiles of west rail at BCR Test Site 4 before and after September 1986 test grinding

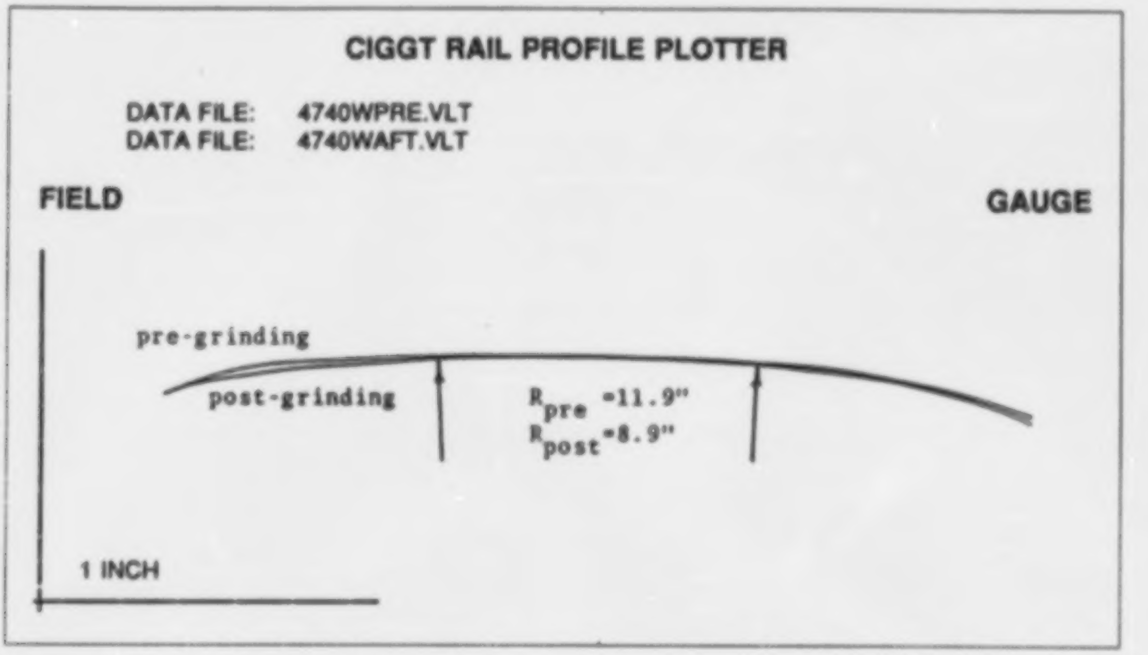


Figure E.18: Measured profiles of west rail at BCR Test Site 5 before and after September 1986 test grinding

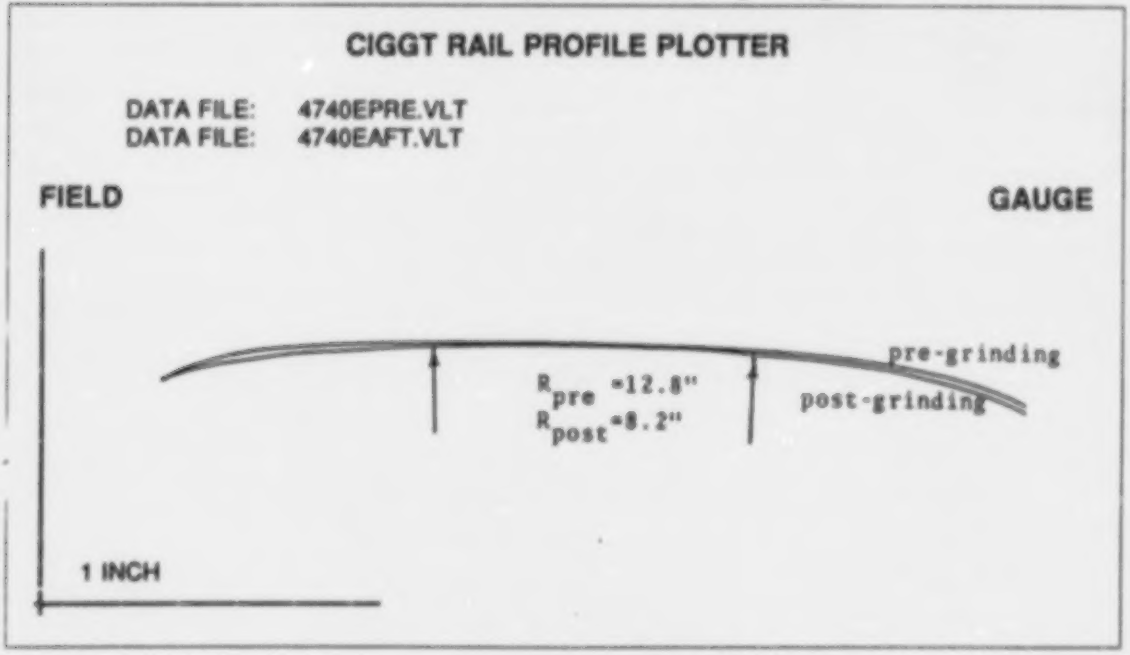


Figure E.19: Measured profiles of east rail at BCR Test Site 5 before and after September 1986 test grinding

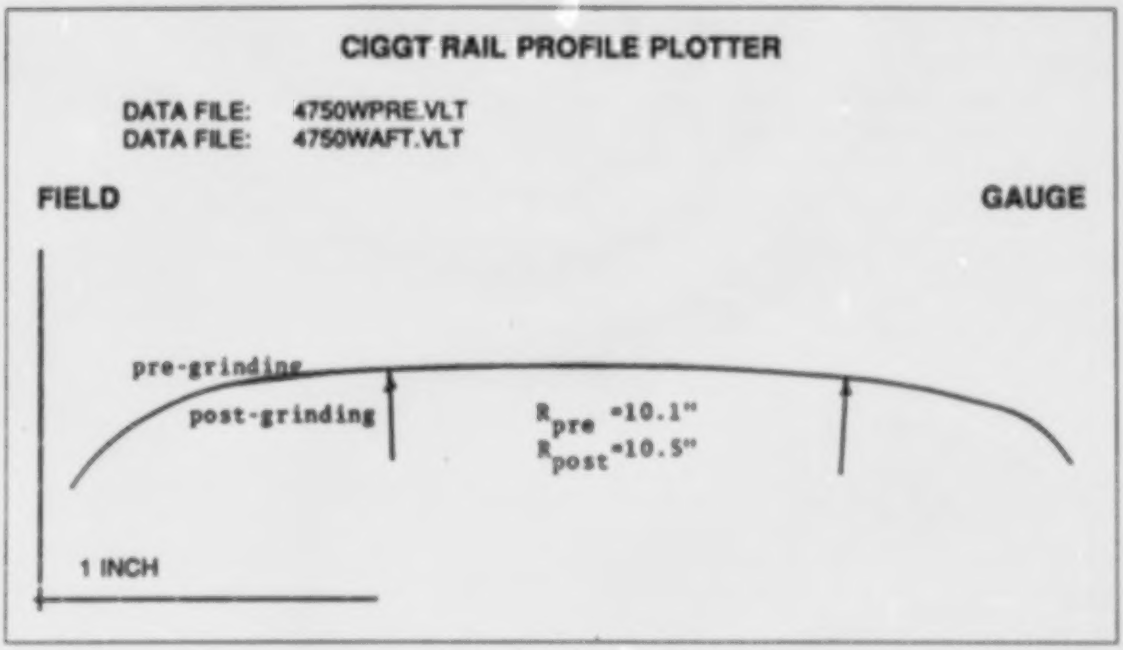


Figure E.20: Measured profiles of west rail at BCR Test Site 6 before and after September 1986 test grinding

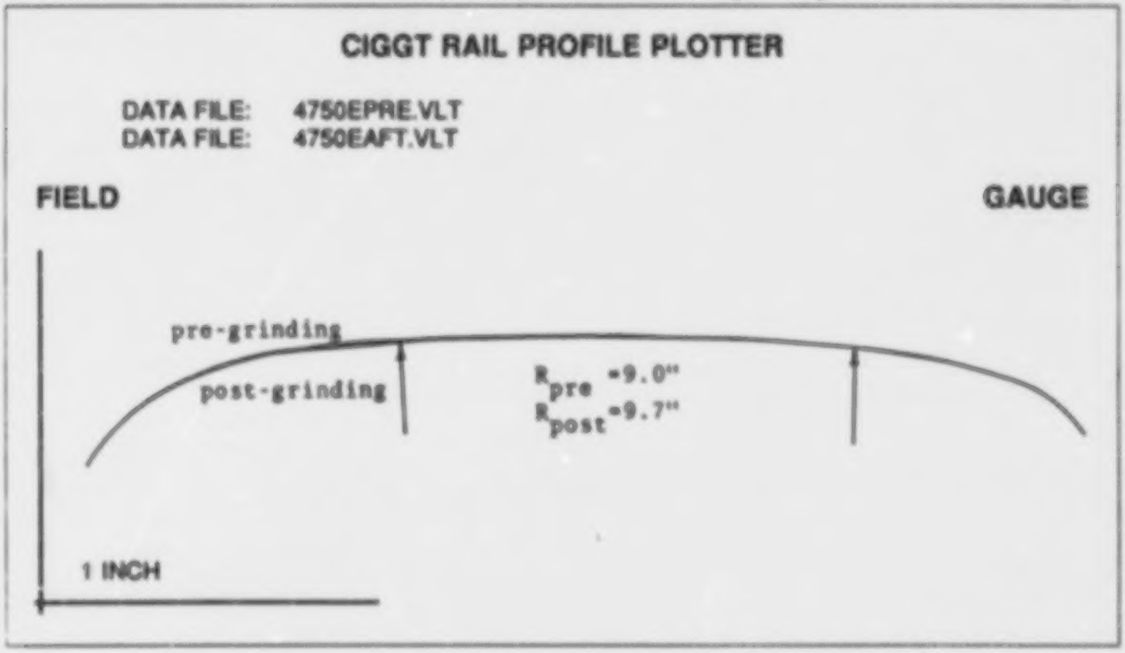


Figure E.21: Measured profiles of east rail at BCR Test Site 6 before and after September 1986 test grinding

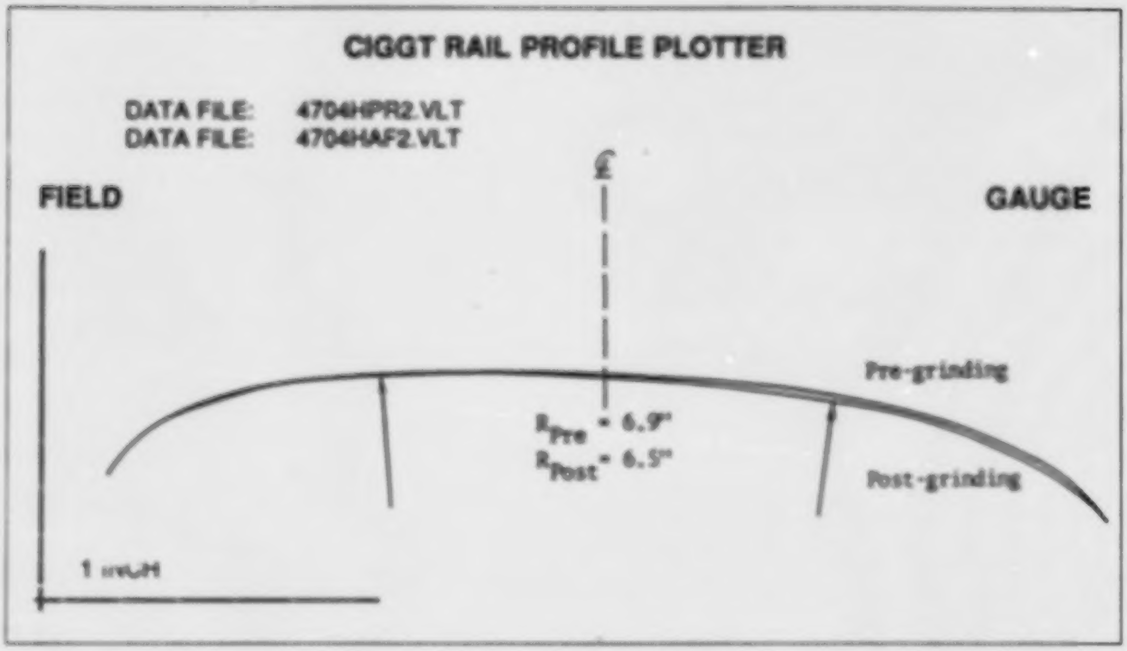


Figure E.22: Measured profiles of high rail at BCR Test Site 1 before and after April 1987 test grinding

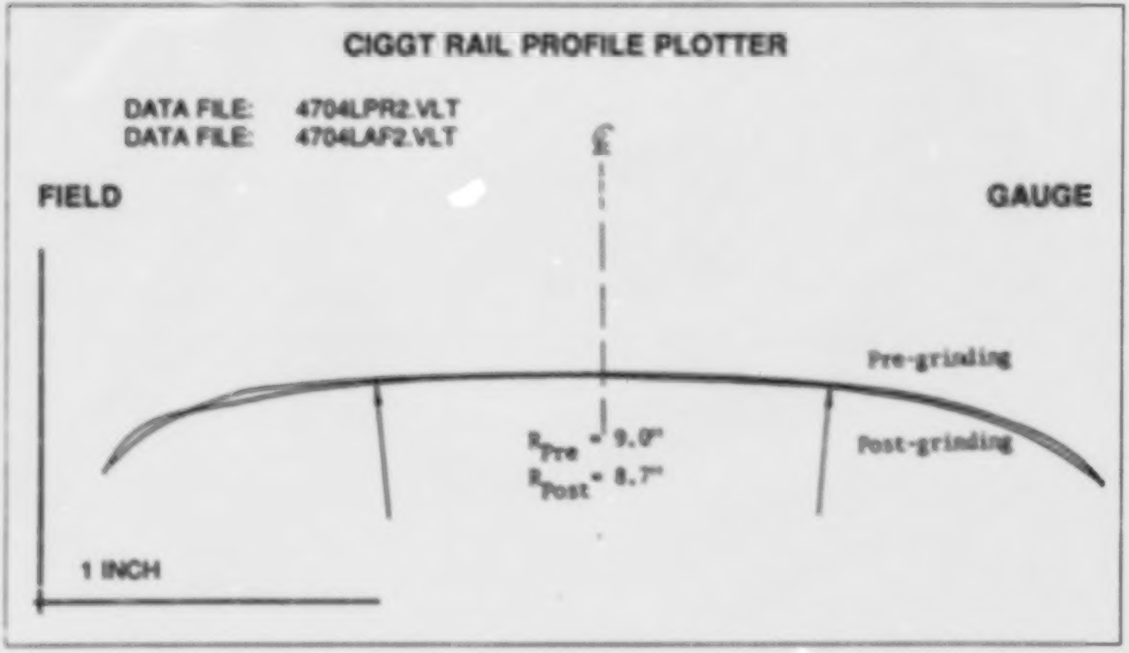


Figure E.23: Measured profiles of low rail at BCR Test Site 1 before and after April 1987 test grinding

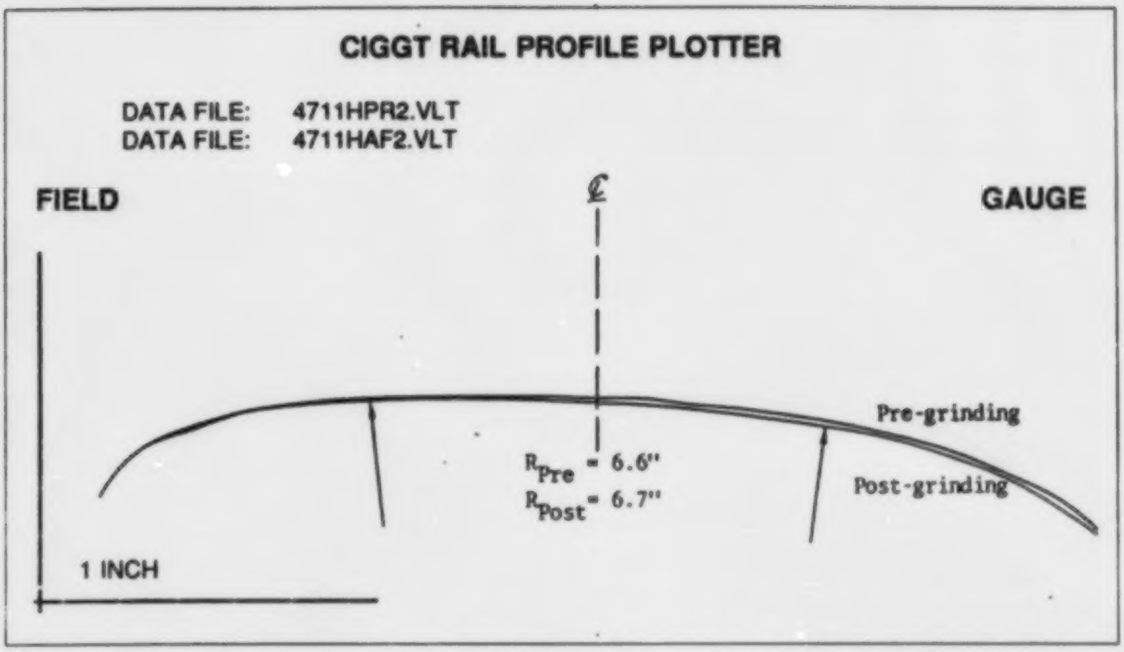


Figure E.24: Measured profiles of high rail at BCR Test Site 3 before and after April 1987 test grinding

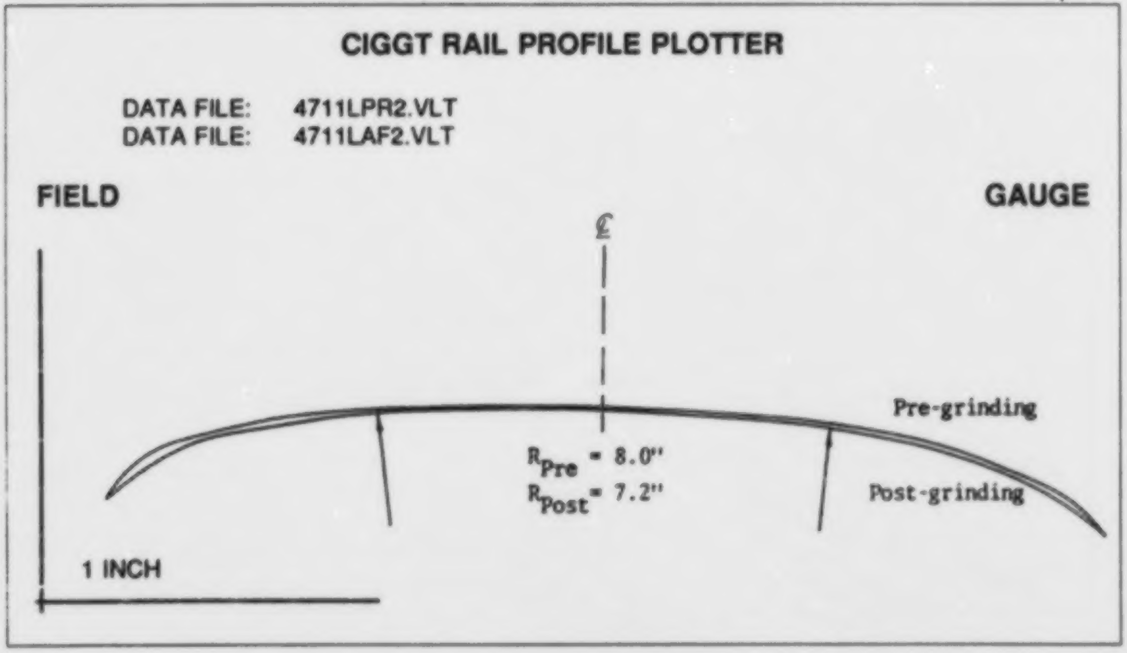


Figure E.25: Measured profiles of low rail at BCR Test Site 3 before and after April 1987 test grinding

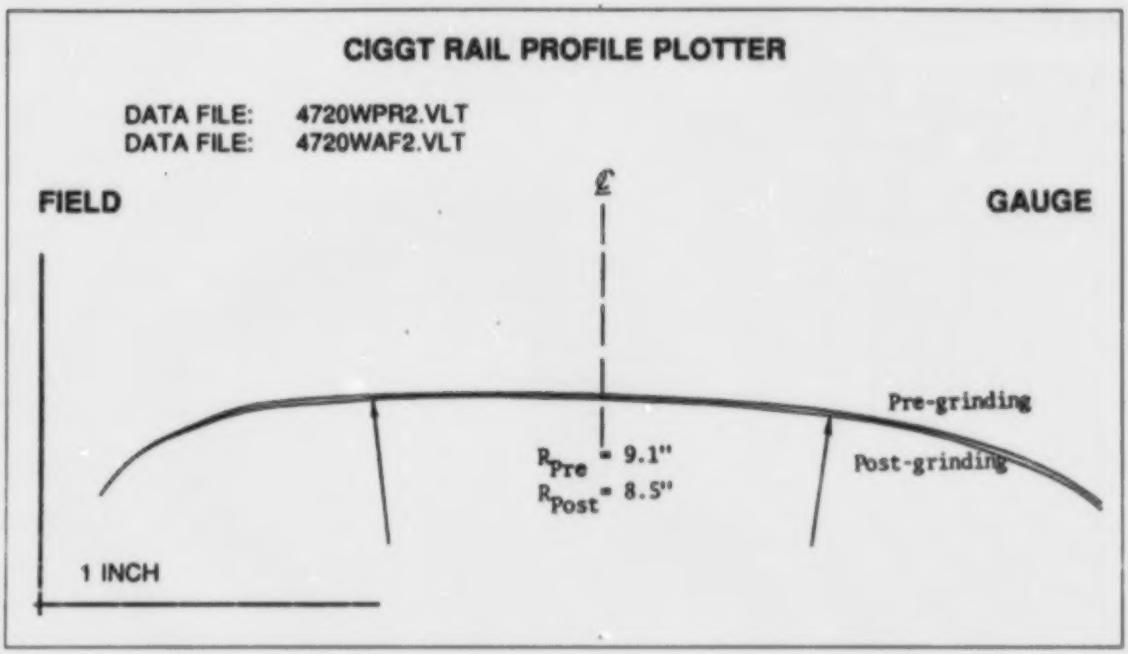


Figure E.26: Measured profiles of west rail at BCR Test Site 4 before and after April 1987 test grinding

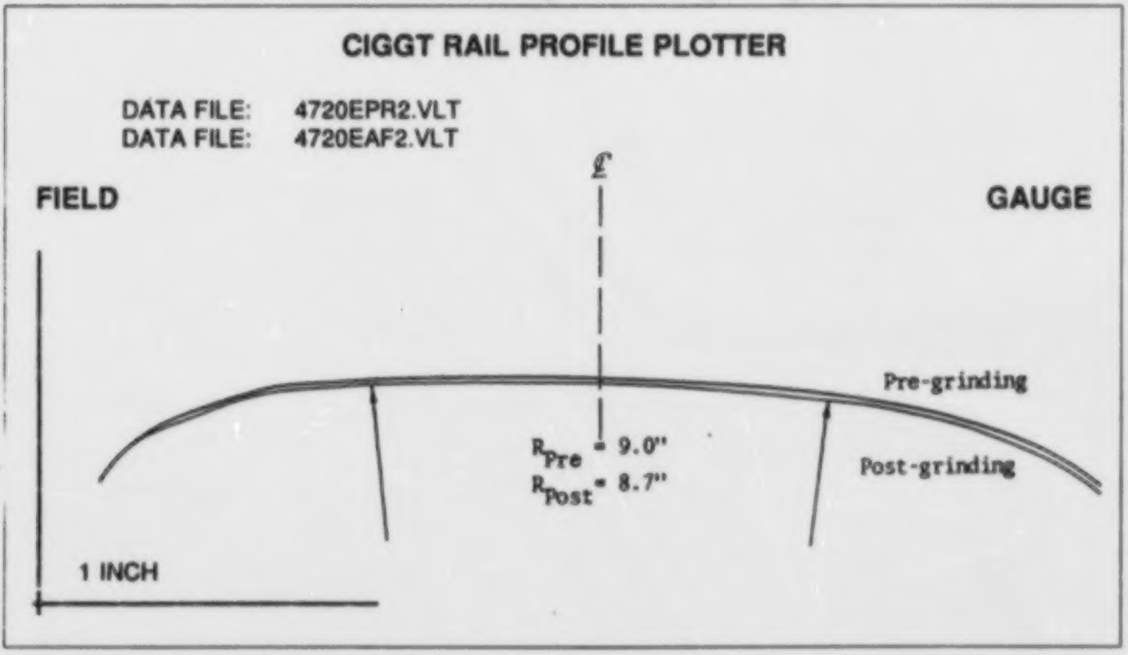


Figure E.27: Measured profiles of east rail at BCR Test Site 4 before and after April 1987 test grinding

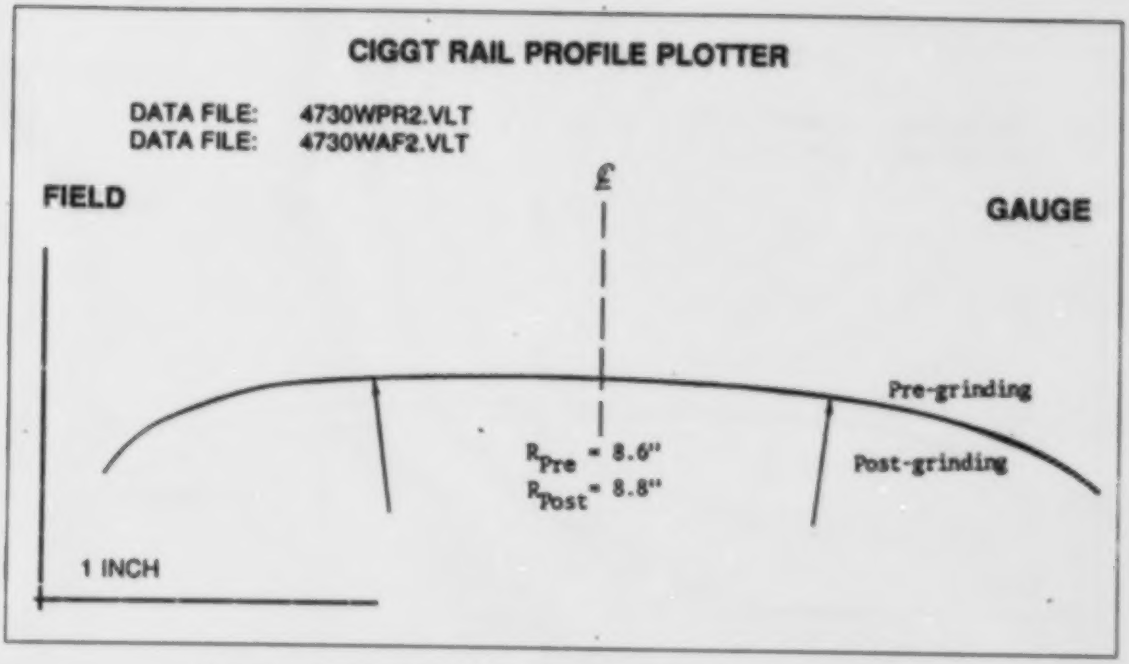


Figure E.28: Measured profiles of west rail at BCR Test Site 4a before and after April 1987 test grinding

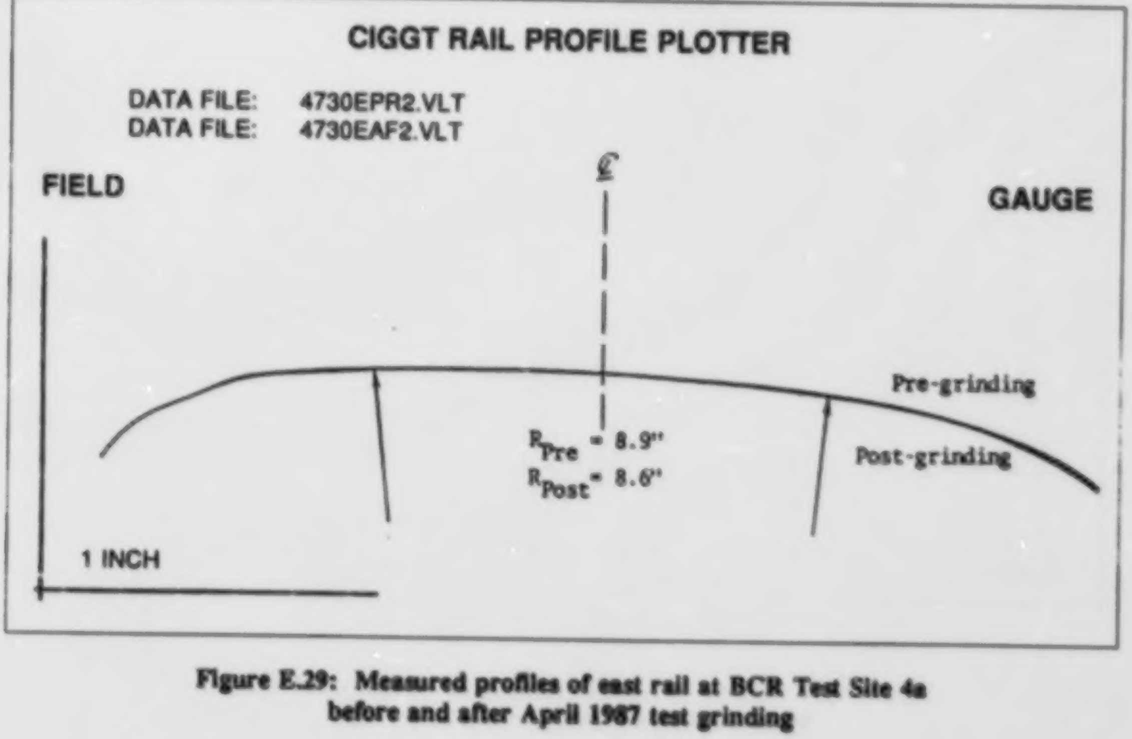


Figure E.29: Measured profiles of east rail at BCR Test Site 4a before and after April 1987 test grinding

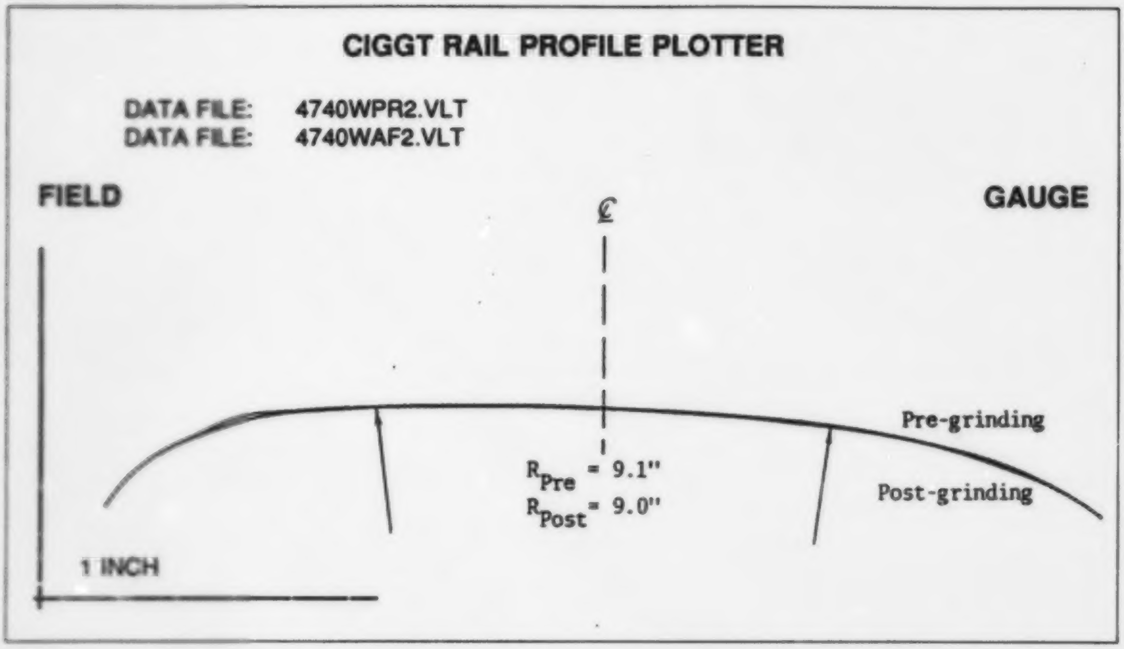


Figure E.30: Measured profiles of west rail at BCR Test Site 5 before and after April 1987 test grinding

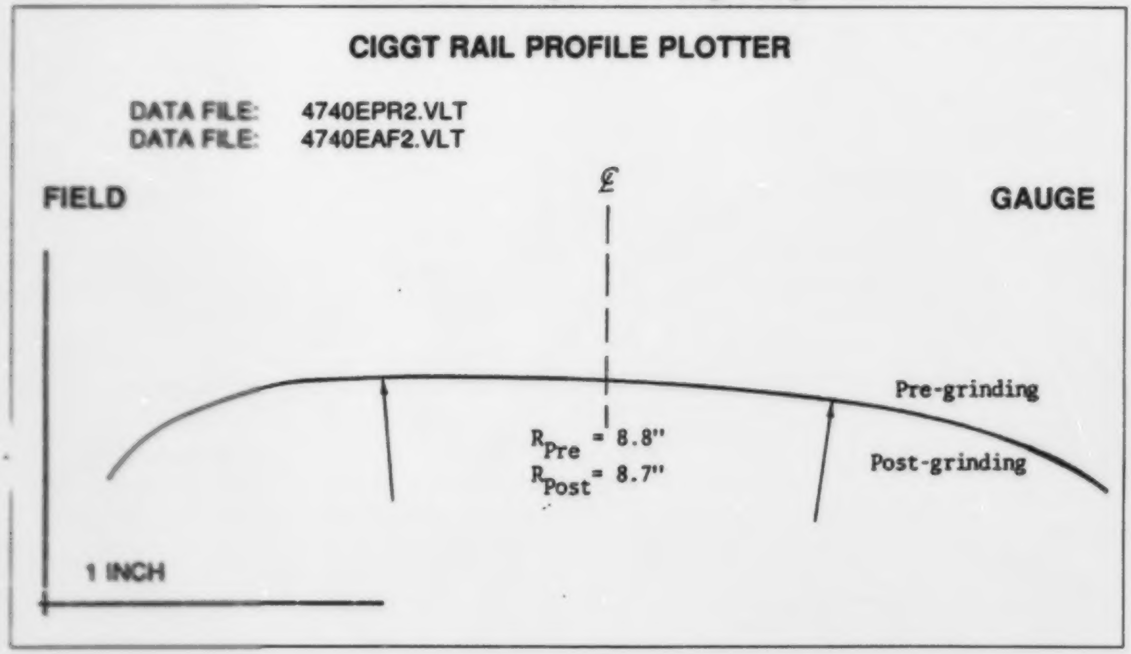


Figure E.31: Measured profiles of east rail at BCR Test Site 5 before and after April 1987 test grinding

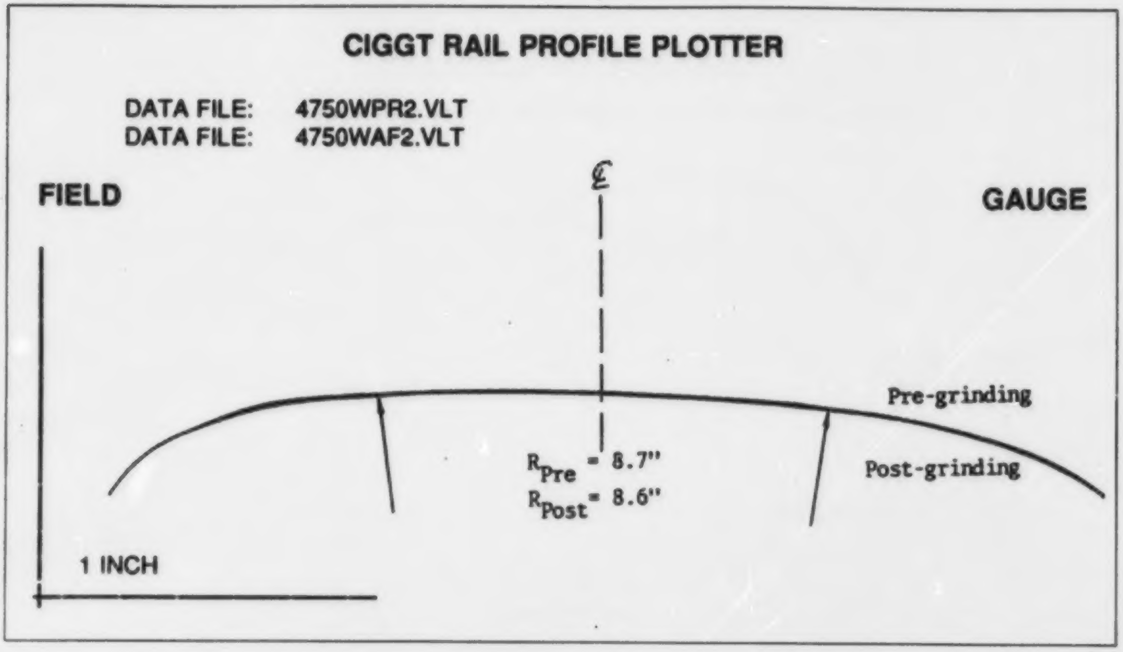


Figure E.32: Measured profiles of west rail at BCR Test Site 6 before and after April 1987 test grinding

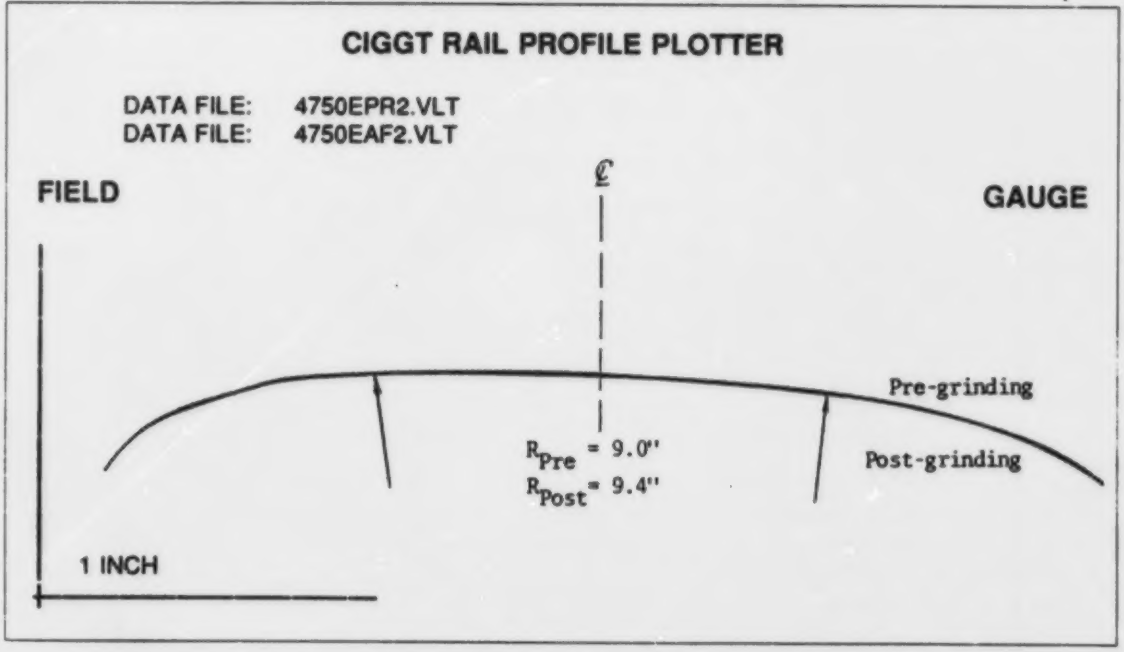


Figure E.33: Measured profiles of east rail at BCR Test Site 6 before and after April 1987 test grinding

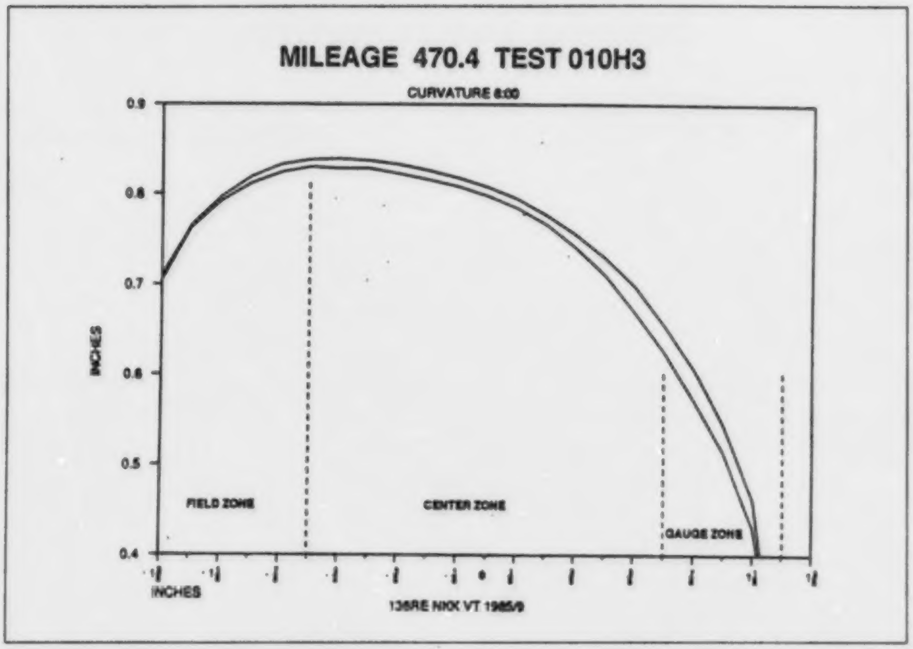


Figure E.34: Measured profiles of the high rail at BCR Test Site 1 before and after November 1987 test grinding

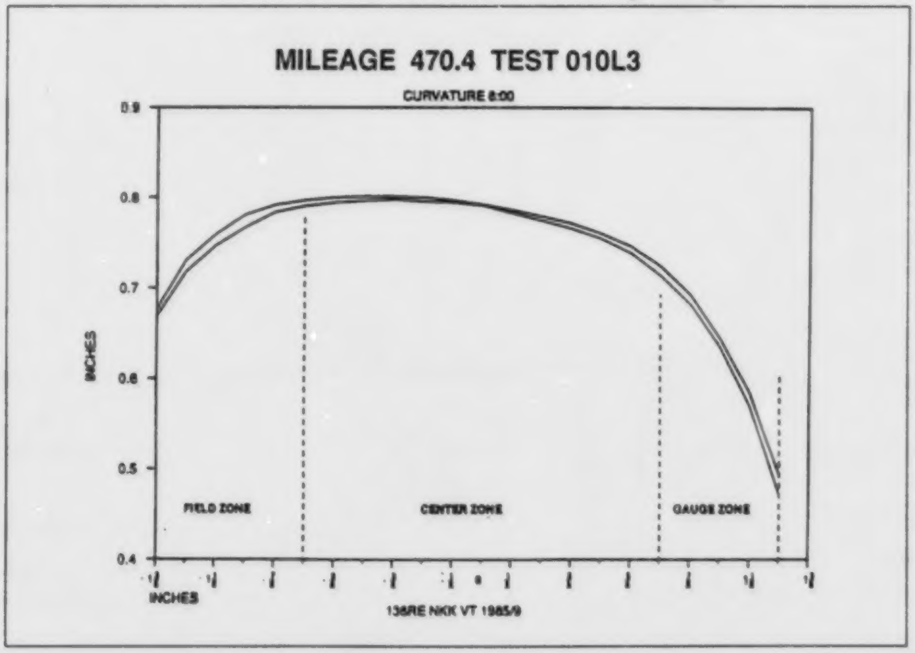


Figure E.35: Measured profiles of the low rail at BCR Test Site 1 before and after November 1987 test grinding

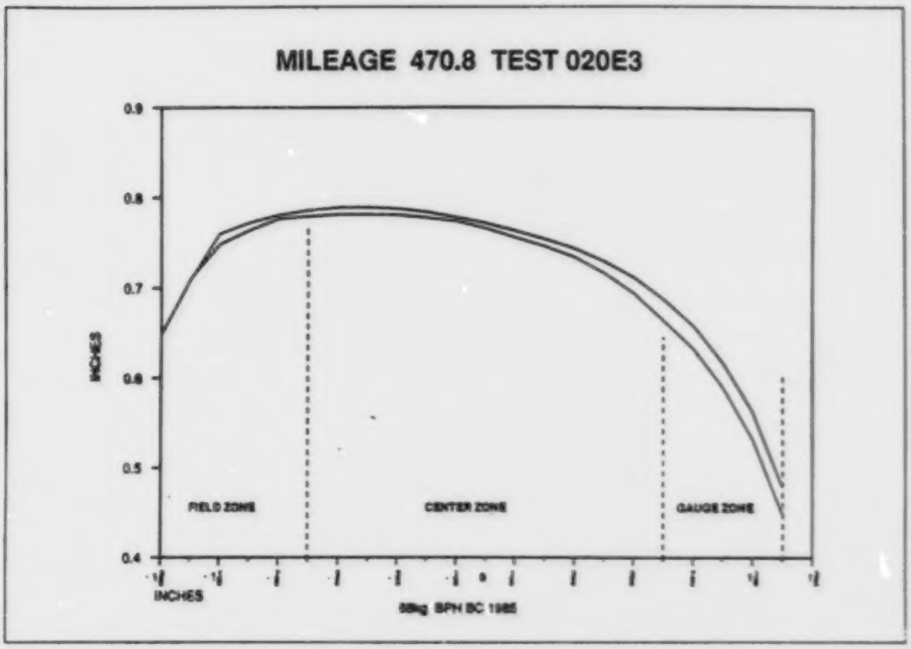


Figure E.36: Measured profiles of the east rail at BCR Test Site 2 before and after November 1987 test grinding

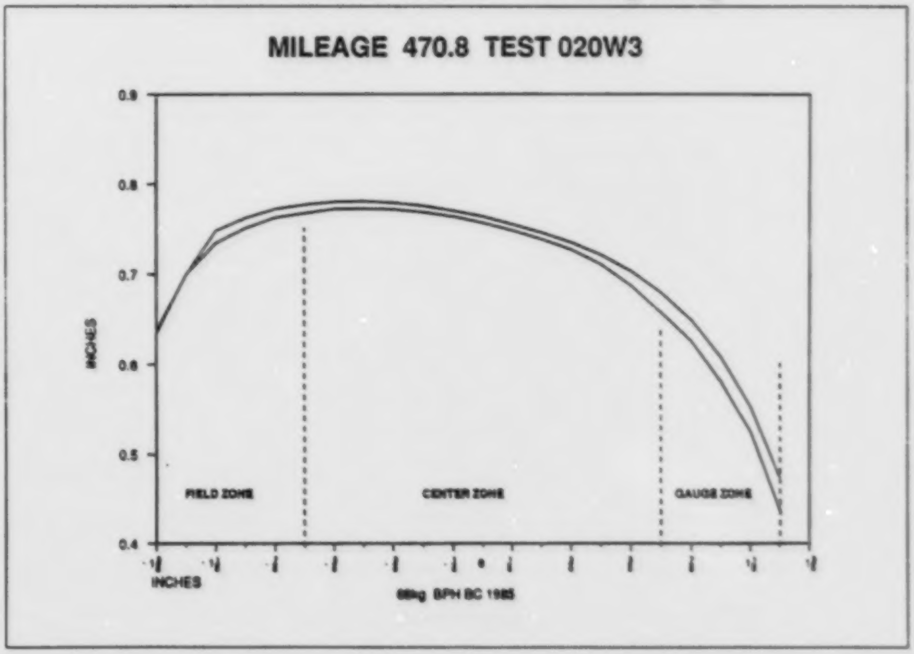


Figure E.37: Measured profiles of the west rail at BCR Test Site 2 before and after November 1987 test grinding

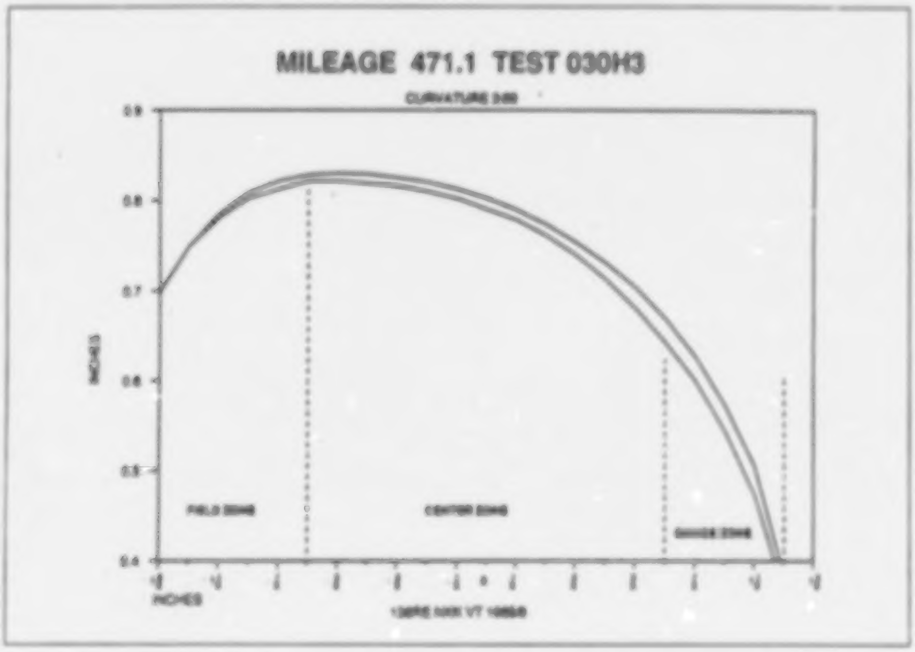


Figure E.38: Measured profiles of the high rail at BCR Test Site 3 before and after November 1987 test grinding

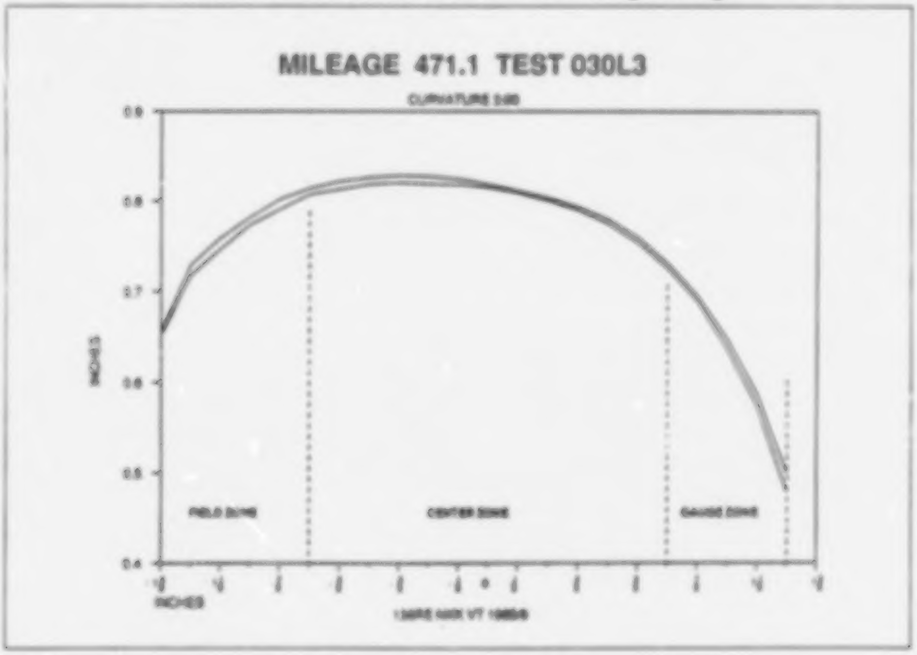


Figure E.39: Measured profiles of the low rail at BCR Test Site 3 before and after November 1987 test grinding

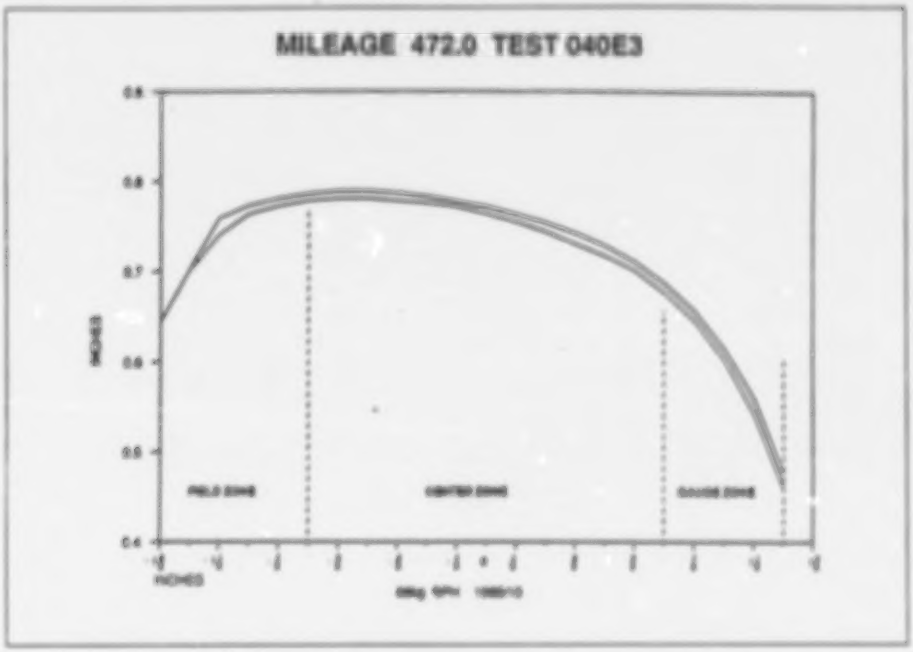


Figure E.40: Measured profiles of the east rail at BCR Test Site 4 before and after November 1987 test grinding

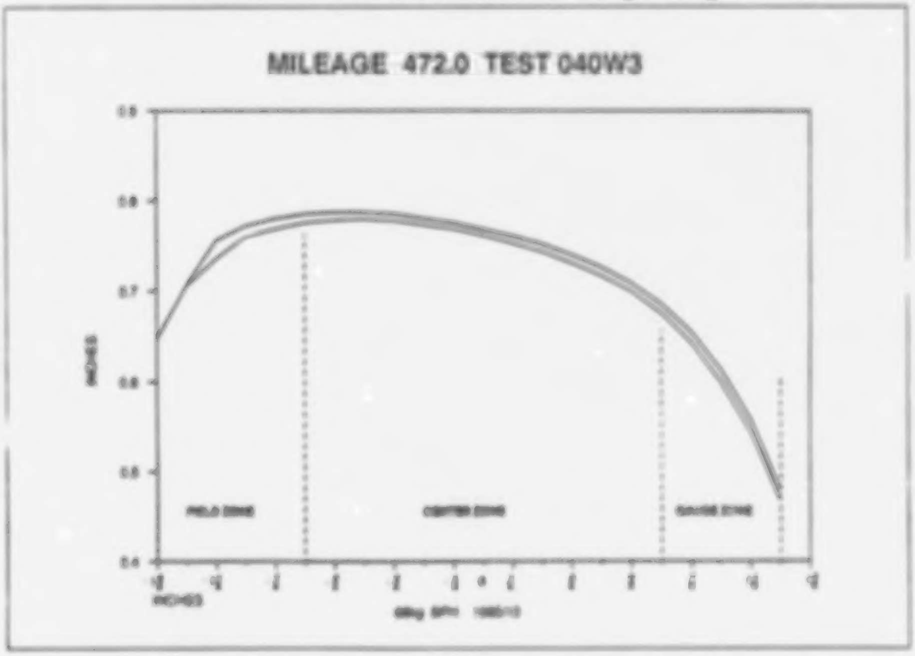


Figure E.41: Measured profiles of the west rail at BCR Test Site 4 before and after November 1987 test grinding

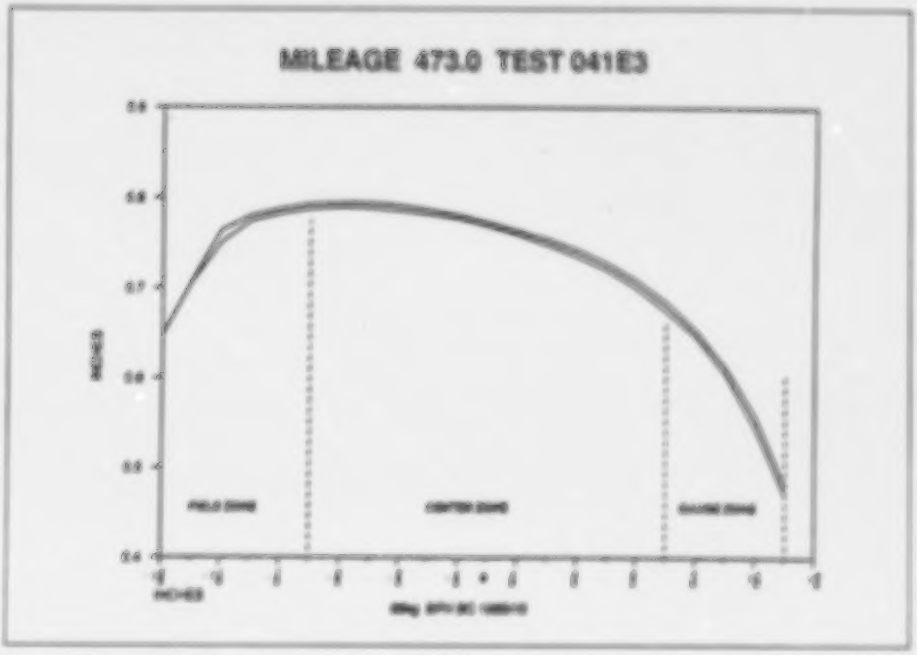


Figure E.42: Measured profiles of the east rail at BCR Test Site 4a before and after November 1987 test grinding

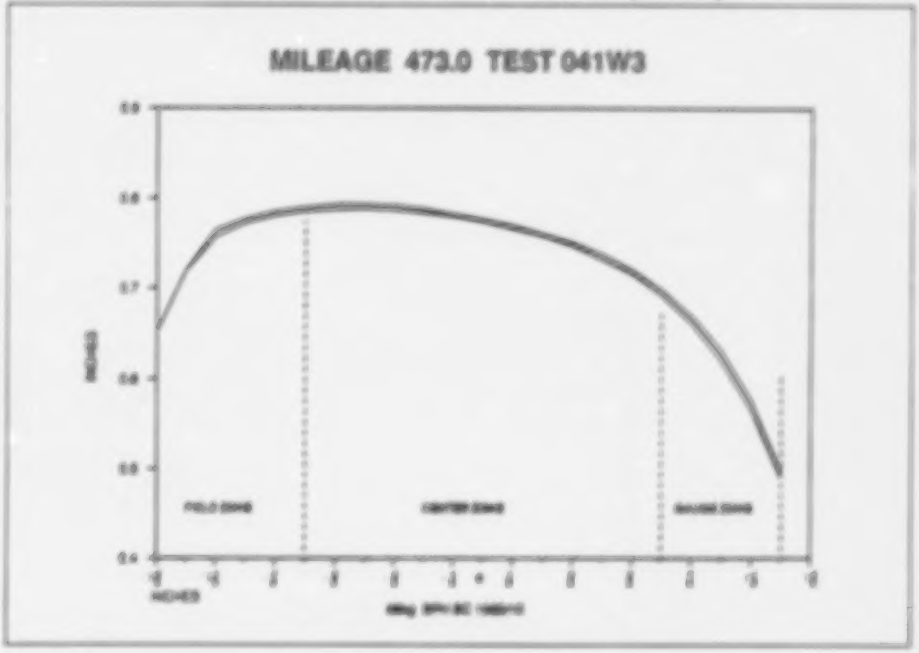


Figure E.43: Measured profiles of the west rail at BCR Test Site 4a before and after November 1987 test grinding

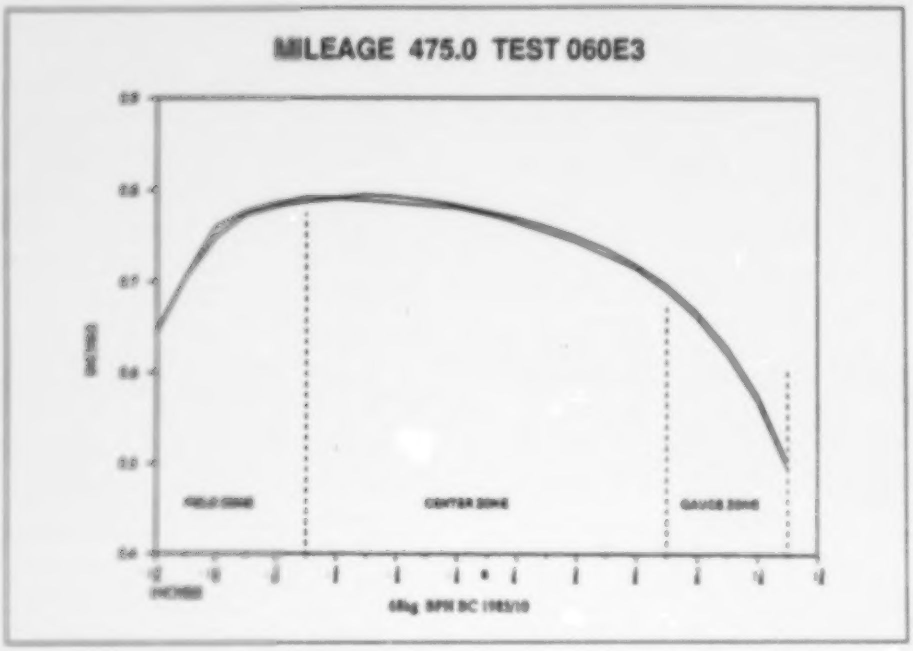


Figure E.44: Measured profiles of the east rail at BCR Test Site 6 before and after November 1987 test grinding

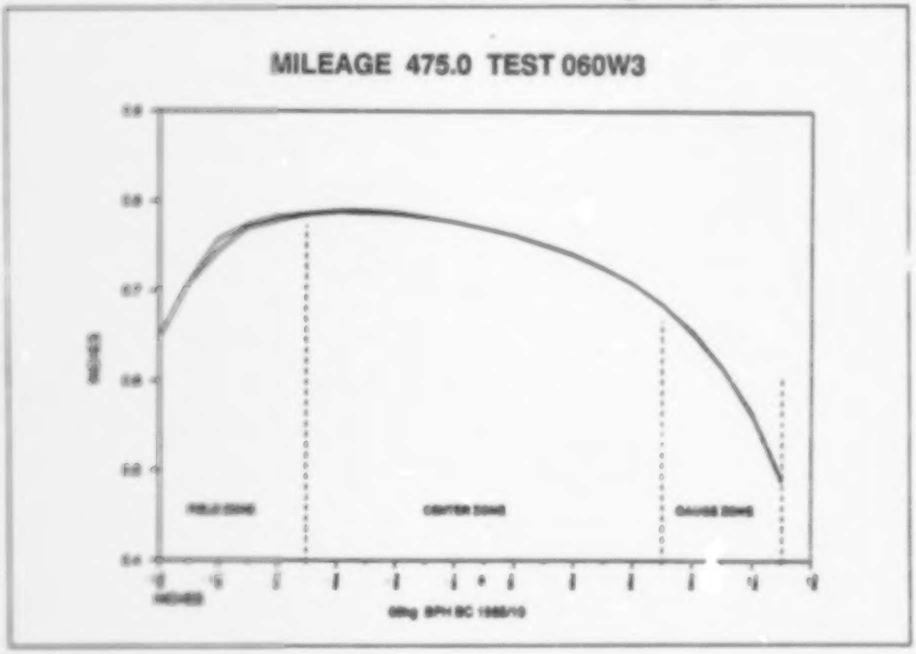


Figure E.45: Measured profiles of the west rail at BCR Test Site 6 before and after November 1987 test grinding

APPENDIX F

PREVENTIVE MAINTENANCE GRINDING

DETAILS OF RAIL GRINDING RATES

Table F.1: Rail Grinding Rates for CPR September 1986 Test

Site Description	Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed (in.^{3}/in.)
RHC, MP 55.5, high rail, 136 lb/yd, Algoma, 1983, 4 passes at 3 mph	field	6	0.049	0.030
	centre	9	0.048	0.048
	gauge	8	0.053	0.047
	total head	21	0.050	0.125
RHC, MP 55.5, low rail, 136 lb/yd, Algoma, 1973, 4 passes at 3 mph	field	6	0.062	0.037
	centre	9	0.032	0.031
	gauge	8	0.032	0.030
	total head	21	0.040	0.098
LHC, MP 55.8, high rail, 136 lb/yd, super, 1984, 1 pass at 3 mph	field	6	0.004	0.002
	centre	9	0.009	0.009
	gauge	8	0.005	0.004
	total head	21	0.006	0.015
LHC, MP 55.8, low rail, 136 lb/yd, super, 1984, 1 pass at 3 mph	field	6	0.004	0.003
	centre	9	0.003	0.003
	gauge	8	0.007	0.006
	total head	21	0.005	0.012

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table F.2: Results of Corrugation Measurements during CPR September 1986 Tests

Station No.	1	2	3	4	5
Corrugation Depth (in.)	0.020	0.014	0.012	0.018	0.014
Wavelength (in.)	19	12	9	15	10

Table F.3: Rail Grinding Rates for BCR September 1986 Tests

Site Description	Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed (in.²/in.)
Right-hand curve, MP 470.4, high rail, 136 lb/yd, NKK VT, 1985, 1 pass at 2 mph	field	4	0.006	0.002
	centre	11	0.010	0.013
	gauge	8	0.025	0.024
	total head	21	0.015	0.039
Right-hand curve, MP 470.4, low rail, 136 lb/yd, NKK VT, 1985, 1 pass at 2 mph	field	6	0.024	0.016
	centre	11	0.008	0.009
	gauge	5	0.022	0.011
	total head	20	0.016	0.036
Tangent, MP 470.8, west rail, 68 kg/m, BHP SC, 1985, 1 pass at 2 mph	field	5	0.006	0.005
	centre	11	0.007	0.008
	gauge	5	0.021	0.010
	total head	19	0.011	0.023
Tangent, MP 470.8, east rail, 68 kg/m, BHP SC, 1985, 1 pass at 2 mph	field	5	0.010	0.006
	centre	11	0.008	0.009
	gauge	6	0.021	0.015
	total head	20	0.013	0.030
Left-hand curve, MP 471.1, high rail, 136 lb/yd, NNK VT, 1985, 1 pass at 2 mph	field	3	0.009	0.002
	centre	11	0.006	0.007
	gauge	8	0.022	0.021
	total head	20	0.012	0.030
Left-hand curve, MP 471.1, low rail, 136 lb/yd, NNK VT, 1985, 1 pass at 2 mph	field	6	0.026	0.018
	centre	11	0.007	0.008
	gauge	5	0.023	0.011
	total head	20	0.016	0.037

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table F.4: Speed Grinding Rates for BCR September 1986 Tests

Site Description	Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed (in.^{3}/in.)
Tangent, MP 472.0, west rail, 68 kg/m, BHP BC, 1985, 1 pass at 3 mph	field	6	0.009	0.006
	centre	11	0.007	0.008
	gauge	4	0.003	0.001
	total head	19	0.006	0.015
Tangent, MP 474.0, west rail, 68 kg/m, BHP BC, 1985, 1 pass at 5 mph	field	6	0.010	0.007
	centre	11	0.004	0.005
	gauge	5	0.008	0.004
	total head	20	0.007	0.016
Tangent, MP 474.0, east rail, 68 kg/m, BHP BC, 1985, 1 pass at 5 mph	field	6	0.011	0.008
	centre	11	0.006	0.007
	gauge	5	0.014	0.007
	total head	20	0.009	0.022
Tangent, MP 475.0, west rail, 68 kg/m, BHP BC, 1985, 1 pass at 8 mph	field	6	0.002	0.001
	centre	11	0.001	0.001
	gauge	5	0.000	0.000
	total head	20	0.001	0.002
Tangent, MP 475.0, east rail, 68 kg/m, BHP BC, 1985, 1 pass at 8 mph	field	6	0.003	0.002
	centre	11	0.002	0.003
	gauge	5	0.000	0.000
	total head	20	0.002	0.005

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table F.5: Rail Grinding Rates for BCR Test Sites 1 and 2 During April 1987 Tests

Site Description	Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed (in.^{3}/in.)
Right-hand curve, MP 470.4, high rail, 136 lb/yd, NKK VT, 1985, 1 pass at 3 mph	field	6	0.003	0.002
	centre	13	0.009	0.013
	gauge	6	0.012	0.008
	total head	23	0.008	0.023
Right-hand curve, MP 470.4, low rail, 136 lb/yd, NKK VT, 1985, 1 pass at 3 mph	field	6	0.013	0.009
	centre	13	0.006	0.009
	gauge	6	0.011	0.007
	total head	23	0.009	0.025
Left-hand curve, MP 471.1, high rail, 136 lb/yd, NKK VT, 1985, 1 pass at 3 mph	field	6	0.002	0.001
	centre	13	0.008	0.012
	gauge	6	0.012	0.008
	total head	23	0.008	0.021
Left-hand curve, MP 471.1, low rail, 136 lb/yd, NKK VT, 1985, 1 pass at 3 mph	field	6	0.015	0.010
	centre	13	0.008	0.011
	gauge	6	0.012	0.008
	total head	23	0.010	0.029

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* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table F.6: Speed Rail Grinding Rates for BCR Test Sites 4, 4a, 5 and 6 during April 1987 Tests

Site Description	Zone	No. of Readings*	Average Grinding Depth, All Passes (in.)	Volume of Metal Removed (in.^{3}/in.)
Tangent, MP 472.0, west rail, 68 kg/m, BHP BC, 1985, 1 pass at 4 mph	field	6	0.007	0.005
	centre	13	0.009	0.014
	gauge	6	0.012	0.008
	total head	23	0.009	0.027
Tangent, MP 472,0, east rail, 68 kg/m, BHP BC, 1985, 1 pass at 4 mph	field	6	0.006	0.004
	centre	13	0.010	0.014
	gauge	6	0.013	0.008
	total head	23	0.010	0.026
Tangent, MP 473.0, west rail, 68 kg/m, BHP BC, 1985, 1 pass at 6 mph	field	6	0.004	0.003
	centre	13	0.005	0.007
	gauge	6	0.005	0.004
	total head	23	0.005	0.014
Tangent, MP 473.0, east rail, 68 km/m, BHP BC, 1985, 1 pass at 6 mph	field	6	0.003	0.002
	centre	13	0.003	0.005
	gauge	6	0.006	0.003
	total head	23	0.004	0.010
Tangent, MP 474.0, west rail, 68 kg/m, BHP BC, 1985, 1 pass at 8 mph	field	6	0.005	0.003
	centre	13	0.002	0.007
	gauge	6	0.005	0.003
	total head	23	0.004	0.013
Tangent, MP 474.0, east rail, 68 kg/m, BHP BC, 1985, 1 pass at 8 mph	field	6	0.002	0.001
	centre	13	0.004	0.006
	gauge	6	0.005	0.003
	total head	23	0.004	0.010
Tangent, MP 475.0, east rail, 68 kg/m, BHP BC, 1985, 1 pass at 10 mph	field	6	0.003	0.002
	centre	13	0.005	0.007
	gauge	6	0.005	0.003
	total head	23	0.004	0.012
Tangent, MP 475.0, east rail, 68 kg/m, BHP BC, 1985, 1 pass at 10 mph	field	6	0.003	0.002
	centre	13	0.004	0.006
	gauge	6	0.004	0.003
	total head	23	0.004	0.011

* A number of depth readings may overlap at the field/centre and centre/gauge boundaries.

Table F.7: Site for High Rail at BCR Test Site 1, November 1987 Test (Test Site 010H3)

Calculations	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Radius Field	2.036		2.257			
Radius Centre	4.681		4.086			
Radius Gauge	0.676		0.247			
Area Field			0.004			
Area Centre			0.020			
Area Gauge			0.013			
Depth Field			0.006			
Depth Centre			0.013			
Depth Gauge			0.025			

Centre O/S	Field Measurements (inches)					
	10H3P0	P1	P2	P3	P4	P5
-1.500	0.615		0.564			
-1.375	0.710		0.705			
-1.250	0.766		0.763			
-1.125	0.797		0.793			
-1.000	0.819		0.812			
-0.875	0.833		0.824			
-0.750	0.838		0.830			
-0.625	0.939		0.829			
-0.500	0.837		0.829			
-0.375	0.833		0.823			
-0.250	0.826		0.816			
-0.125	0.818		0.809			
0.000	0.808		0.798			
0.125	0.795		0.785			
0.250	0.777		0.767			
0.375	0.756		0.742			
0.500	0.730		0.711			
0.625	0.699		0.671			
0.750	0.655		0.625			
0.875	0.606		0.571			
1.000	0.545		0.515			
1.125	0.463		0.431			
1.250	0.223		0.243			
1.375						

Other Data	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Grinding Pattern		Relief	NRC rev			
Speed miles/hour		3.0	3.0			

Comments:	LORAM 44 Stone Grinder; 2 passes
Data Collected:	Nov '87, mile 470.4, Chetwynd S/D

Table F.8: Low Rail at Test Site 1
(Test Site 010L3)

Calculations	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Radius Field Radius Centre Radius Gauge	2.199 8.669 1.205		2.096 7.626 0.677			
Area Field Area Centre Area Gauge			0.007 0.007 0.006			
Depth Field Depth Centre Depth Gauge			0.011 0.005 0.013			

Centre O/S	Field Measurements (inches)					
	10L3P0	P1	P2	P3	P4	P5
-1.500	0.569		0.566			
-1.375	0.677		0.669			
-1.250	0.731		0.718			
-1.125	0.759		0.747			
-1.000	0.781		0.767			
-0.875	0.792		0.784			
-0.750	0.797		0.791			
-0.625	0.800		0.795			
-0.500	0.801		0.797			
-0.375	0.801		0.798			
-0.250	0.800		0.796			
-0.125	0.797		0.795			
0.000	0.792		0.791			
0.125	0.786		0.783			
0.250	0.779		0.775			
0.375	0.771		0.766			
0.500	0.760		0.754			
0.625	0.746		0.739			
0.750	0.724		0.714			
0.875	0.693		0.682			
1.000	0.644		0.636			
1.125	0.584		0.570			
1.250	0.494		0.473			
1.375						

Other Data	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Grinding Pattern Speed miles/hour		Relief 3.0	NRC rev 3.0			

Comments:	LORAM 44 Stone Grinder; 2 passes
Data Collected:	Nov '97, mile 470.4, Chetwynd S/D

Table F.9: East #2
(Test Site 020E3)

Calculations	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Radius Field Radius Centre Radius Gauge	1.245 7.763 1.212	1.584 6.331 0.862				
Area Field Area Centre Area Gauge		0.003 0.014 0.014				
Depth Field Depth Centre Depth Gauge		0.006 0.009 0.027				

Centre O/S	Field Measurements (inches)					
	20E3P0	P1	P2	P3	P4	P5
-1.500	0.512	0.511				
-1.375	0.649	0.648				
-1.250	0.709	0.710				
-1.125	0.760	0.749				
-1.000	0.772	0.764				
-0.875	0.781	0.777				
-0.750	0.786	0.780				
-0.625	0.789	0.782				
-0.500	0.789	0.782				
-0.375	0.788	0.781				
-0.250	0.784	0.778				
-0.125	0.778	0.774				
0.000	0.771	0.766				
0.125	0.763	0.755				
0.250	0.754	0.746				
0.375	0.743	0.734				
0.500	0.729	0.716				
0.625	0.711	0.694				
0.750	0.687	0.664				
0.875	0.636	0.633				
1.000	0.617	0.590				
1.125	0.563	0.533				
1.250	0.479	0.449				
1.375						

Other Data	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Grinding Pattern Speed miles/hour		HRC rev 3.0				

Comments:	LORAM 44 Stone Grinder
Data Collected:	Nov '87, mile 470.8 Chetwynd S/O

Table F.10 West #2
(Test Site 020W3)

Calculations	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Radius Field	1.293	1.829				
Radius Centre	7.761	6.136				
Radius Gauge	1.335	0.825				
Area Field		0.005				
Area Centre		0.014				
Area Gauge		0.014				
Depth Field		0.008				
Depth Centre		0.009				
Depth Gauge		0.026				

Centre O/S	Field Measurements (inches)					
	20W3P0	P1	P2	P3	P4	P5
-1.500	0.508	0.505				
-1.375	0.638	0.634				
-1.250	0.699	0.700				
-1.125	0.748	0.736				
-1.000	0.762	0.751				
-0.875	0.772	0.763				
-0.750	0.777	0.768				
-0.625	0.780	0.772				
-0.500	0.781	0.773				
-0.375	0.779	0.772				
-0.250	0.776	0.769				
-0.125	0.770	0.764				
0.000	0.764	0.757				
0.125	0.755	0.749				
0.250	0.746	0.739				
0.375	0.736	0.727				
0.500	0.721	0.711				
0.625	0.703	0.688				
0.750	0.680	0.657				
0.875	0.649	0.625				
1.000	0.608	0.581				
1.125	0.563	0.526				
1.250	0.474	0.438				
1.375						

Other Data	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Grinding Pattern		NRC rev				
Speed miles/hour		3.0				

Comments: LORAM 44 Stone Grinder
Data Collected: Nov '87, mile 470.8 Chetwynd S/D

Table F.11 High #3
(Test Site 030H3)

Calculations	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Radius Field	1.900		2.132			
Radius Centre	5.326		4.828			
Radius Gauge	1.041		0.857			
Area Field			0.003			
Area Centre			0.020			
Area Gauge			0.014			
Depth Field			0.005			
Depth Centre			0.013			
Depth Gauge			0.026			

Centre O/S	Field Measurements (inches)					
	30H3P0	P1	P2	P3	P4	P5
-1.500	0.565		0.562			
-1.375	0.700		0.698			
-1.250	0.750		0.749			
-1.125	0.785		0.781			
-1.000	0.809		0.803			
-0.875	0.822		0.813			
-0.750	0.828		0.822			
-0.625	0.830		0.822			
-0.500	0.829		0.819			
-0.375	0.825		0.816			
-0.250	0.820		0.810			
-0.125	0.812		0.802			
0.000	0.802		0.790			
0.125	0.789		0.778			
0.250	0.773		0.761			
0.375	0.754		0.740			
0.500	0.731		0.713			
0.625	0.704		0.681			
0.750	0.669		0.643			
0.875	0.626		0.600			
1.000	0.573		0.545			
1.125	0.508		0.475			
1.250	0.385		0.369			
1.375						

Other Data	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Grinding Pattern		Relief	NRC rev			
Speed miles/hour		3.0	3.0			

Comments:	LORAM 44 Stone Grinder; 2 passes
Data Collected:	Nov '87, mile 471.1, Chetwynd S/D

Table F.12 Low #3
(Test Site 030L3)

Calculations	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Radius Field	3.130		3.907			
Radius Centre	5.868		5.834			
Radius Gauge	1.364		0.765			
Area Field			0.006			
Area Centre			0.008			
Area Gauge			0.005			
Depth Field			0.010			
Depth Centre			0.006			
Depth Gauge			0.010			

Centre O/S	Field Measurements (inches)					
	30L3P0	P1	P2	P3	P4	P5
-1.500	0.570		0.561			
-1.375	0.656		0.652			
-1.250	0.729		0.718			
-1.125	0.759		0.747			
-1.000	0.782		0.774			
-0.875	0.802		0.791			
-0.750	0.814		0.808			
-0.625	0.822		0.813			
-0.500	0.826		0.819			
-0.375	0.828		0.820			
-0.250	0.827		0.819			
-0.125	0.824		0.818			
0.000	0.818		0.815			
0.125	0.811		0.809			
0.250	0.803		0.800			
0.375	0.793		0.790			
0.500	0.779		0.775			
0.625	0.759		0.754			
0.750	0.730		0.725			
0.875	0.694		0.689			
1.000	0.647		0.637			
1.125	0.585		0.573			
1.250	0.429		0.479			
1.375						

Other Data	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Grinding Pattern		Relief	NRC rev			
Speed miles/hour		3.0	3.0			

Comments: LORAM 44 Stone Grinder; 2 passes
Data Collected: Nov '87, mile 471.1, Chetwynd S/D

Table F.13 East #4
(Test Site 040E3)

Calculations	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Radius Field Radius Centre Radius Gauge	1.133 7.883 1.247	1.558 7.887 0.874				
Area Field Area Centre Area Gauge		0.005 0.013 0.006				
Depth Field Depth Centre Depth Gauge		0.008 0.009 0.013				

Centre O/S	Field Measurements (inches)					
	40E3P0	P1	P2	P3	P4	P5
-1.500	0.515	0.512				
-1.375	0.644	0.645				
-1.250	0.704	0.702				
-1.125	0.759	0.741				
-1.000	0.773	0.764				
-0.875	0.781	0.773				
-0.750	0.786	0.779				
-0.625	0.789	0.781				
-0.500	0.789	0.781				
-0.375	0.787	0.778				
-0.250	0.783	0.776				
-0.125	0.777	0.771				
0.000	0.771	0.764				
0.125	0.763	0.754				
0.250	0.754	0.744				
0.375	0.742	0.730				
0.500	0.728	0.717				
0.625	0.710	0.701				
0.750	0.687	0.677				
0.875	0.656	0.646				
1.000	0.615	0.604				
1.125	0.580	0.544				
1.250	0.476	0.462				
1.375						

Other Data	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Grinding Pattern Speed miles/hour		NRC rev 3.0				

Comments:	LORAM 44 Stone Grinder
Data Collected:	Nov '87, mile 472.0, Chetwynd S/D

Table F.14 West #4
(Test Site 040W3)

Calculations	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Radius Field	1.256	2.029				
Radius Centre	8.138	7.705				
Radius Gauge	1.360	1.065				
Area Field		0.006				
Area Centre		0.012				
Area Gauge		0.006				
Depth Field		0.010				
Depth Centre		0.008				
Depth Gauge		0.012				

Centre O/S	Field Measurements (inches)					
	40W3P0	P1	P2	P3	P4	P5
-1.500	0.512	0.515				
-1.375	0.648	0.648				
-1.250	0.707	0.706				
-1.125	0.756	0.736				
-1.000	0.772	0.761				
-0.875	0.780	0.769				
-0.750	0.786	0.776				
-0.625	0.787	0.779				
-0.500	0.787	0.780				
-0.375	0.785	0.778				
-0.250	0.780	0.773				
-0.125	0.775	0.769				
0.000	0.768	0.762				
0.125	0.761	0.753				
0.250	0.752	0.744				
0.375	0.740	0.731				
0.500	0.726	0.717				
0.625	0.708	0.700				
0.750	0.685	0.676				
0.875	0.654	0.643				
1.000	0.612	0.599				
1.125	0.557	0.544				
1.250	0.478	0.468				
1.375						

Other Data	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Grinding Pattern		NRC rev				
Speed miles/hour		3.0				

Comments:	LORAM 44 Stone Grinder
Data Collected:	Nov '87, mile 472.0, Chetwynd S/D

Table F.15 East #4a
(Test Site 041E3)

Calculations	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Radius Field Radius Centre Radius Gauge	1.123 8.019 1.401	1.336 7.680 0.961				
Area Field Area Centre Area Gauge		0.004 0.008 0.004				
Depth Field Depth Centre Depth Gauge		0.006 0.005 0.008				

Centre O/S	Field Measurements (inches)					
	41E3P0	P1	P2	P3	P4	P5
-1.500	0.521	0.514				
-1.375	0.649	0.648				
-1.250	0.709	0.707				
-1.125	0.764	0.751				
-1.000	0.780	0.775				
-0.875	0.788	0.783				
-0.750	0.793	0.788				
-0.625	0.794	0.790				
-0.500	0.794	0.789				
-0.375	0.791	0.786				
-0.250	0.788	0.782				
-0.125	0.780	0.777				
0.000	0.772	0.769				
0.125	0.763	0.759				
0.250	0.754	0.748				
0.375	0.742	0.735				
0.500	0.727	0.721				
0.625	0.708	0.701				
0.750	0.684	0.676				
0.875	0.653	0.648				
1.000	0.612	0.606				
1.125	0.558	0.547				
1.250	0.481	0.472				
1.375						

Other Data	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Grinding Pattern Speed miles/hour		NRC rev 6.0				

Comments:	LORAM 44 Stone Grinder; 100 m south of old site
Data Collected:	Nov '87, mile 473.0, Chetwynd S/D

Table F.16 East #4a
(Test Site 041W3)

Calculations	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Radius Field Radius Centre Radius Gauge	1.424 8.263 1.300	1.634 8.002 1.023				
Area Field Area Centre Area Gauge		0.003 0.006 0.004				
Depth Field Depth Centre Depth Gauge		0.004 0.004 0.007				

Centre O/S	Field Measurements (inches)					
	41W3P0	P1	P2	P3	P4	P5
-1.500	0.511	0.511				
-1.375	0.652	0.653				
-1.250	0.721	0.720				
-1.125	0.765	0.758				
-1.000	0.777	0.773				
-0.875	0.786	0.781				
-0.750	0.790	0.786				
-0.625	0.793	0.788				
-0.500	0.793	0.789				
-0.375	0.792	0.787				
-0.250	0.788	0.784				
-0.125	0.782	0.780				
0.000	0.776	0.774				
0.125	0.769	0.766				
0.250	0.760	0.758				
0.375	0.750	0.747				
0.500	0.737	0.732				
0.625	0.719	0.716				
0.750	0.697	0.693				
0.875	0.668	0.662				
1.000	0.629	0.621				
1.125	0.575	0.567				
1.250	0.497	0.491				
1.375						

Other Data	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Grinding Pattern Speed miles/hour		NRC rev 6.0				

Comments:	LORAM 44 Stone Grinder; 100 m south of old site
Data Collected:	Nov '87, mile 473.0, Chetwynd S/D

Table F.17 East #6
(Test Site 060E3)

Calculations	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Radius Field Radius Centre Radius Gauge	1.169 8.266 1.423	1.383 8.547 1.058				
Area Field Area Centre Area Gauge		0.003 0.007 0.004				
Depth Field Depth Centre Depth Gauge		0.004 0.005 0.007				

Centre O/S	Field Measurements (inches)					
	60E1P0	P1	P2	P3	P4	P5
-1.500	0.516	0.516				
-1.375	0.646	0.644				
-1.250	0.706	0.706				
-1.125	0.760	0.749				
-1.000	0.777	0.774				
-0.875	0.786	0.783				
-0.750	0.792	0.788				
-0.625	0.792	0.791				
-0.500	0.796	0.790				
-0.375	0.793	0.787				
-0.250	0.789	0.784				
-0.125	0.784	0.781				
0.000	0.777	0.774				
0.125	0.769	0.765				
0.250	0.760	0.753				
0.375	0.749	0.743				
0.500	0.735	0.729				
0.625	0.718	0.714				
0.750	0.696	0.690				
0.875	0.667	0.661				
1.000	0.629	0.621				
1.125	0.578	0.571				
1.250	0.506	0.497				
1.375						

Other Data	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Grinding Pattern Speed miles/hour		NRC rev 9.0				

Comments:	LORAM 44 Stone Grinder
Data Collected:	Nov '87, mile 475.0, Chetwynd S/D

Table F.18 West #6
(Test Site 060W3)

Calculations	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Radius Field	1.257	1.586				
Radius Centre	8.011	8.009				
Radius Gauge	1.422	1.085				
Area Field		0.003				
Area Centre		0.002				
Area Gauge		0.002				
Depth Field		0.005				
Depth Centre		0.001				
Depth Gauge		0.003				

Centre O/S	Field Measurements (inches)					
	60W3P0	P1	P2	P3	P4	P5
-1.500	0.521	0.524				
-1.375	0.648	0.649				
-1.250	0.709	0.708				
-1.125	0.757	0.745				
-1.000	0.774	0.771				
-0.875	0.783	0.779				
-0.750	0.787	0.785				
-0.625	0.790	0.788				
-0.500	0.790	0.787				
-0.375	0.788	0.786				
-0.250	0.783	0.782				
-0.125	0.777	0.777				
0.000	0.770	0.770				
0.125	0.762	0.762				
0.250	0.752	0.750				
0.375	0.741	0.740				
0.500	0.726	0.725				
0.625	0.708	0.708				
0.750	0.685	0.685				
0.875	0.656	0.653				
1.000	0.616	0.614				
1.125	0.565	0.561				
1.250	0.491	0.487				
1.375						

Other Data	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5
Grinding Pattern		NRC rev				
Speed miles/hour		9.0				

Comments:	LORAM 44 Stone Grinder
Data Collected:	Nov '87, mile 475.0, Chetwynd S/D

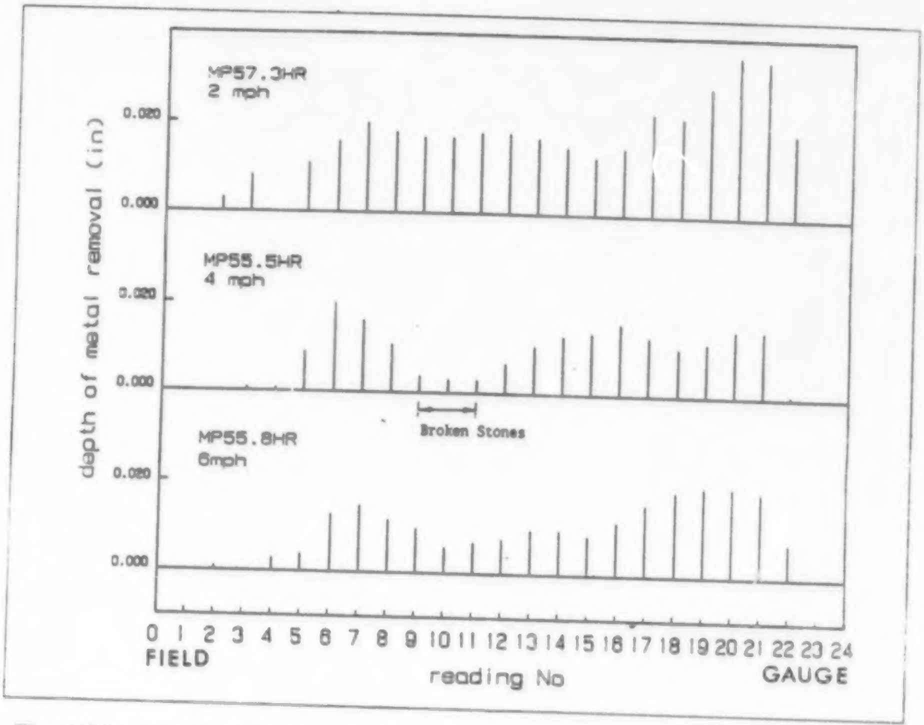

Figure F.1: Grinding rates across the high rails of the CPR test sites during August 1987 test

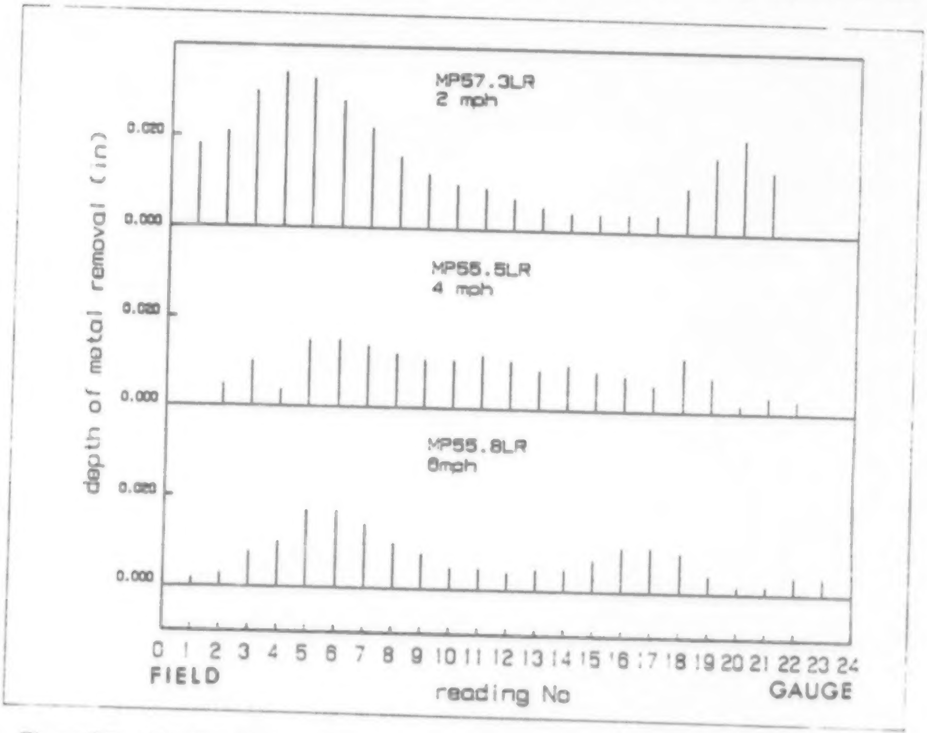

Figure F.2: Grinding rates across the low rails of the CPR test sites during August 1987 test

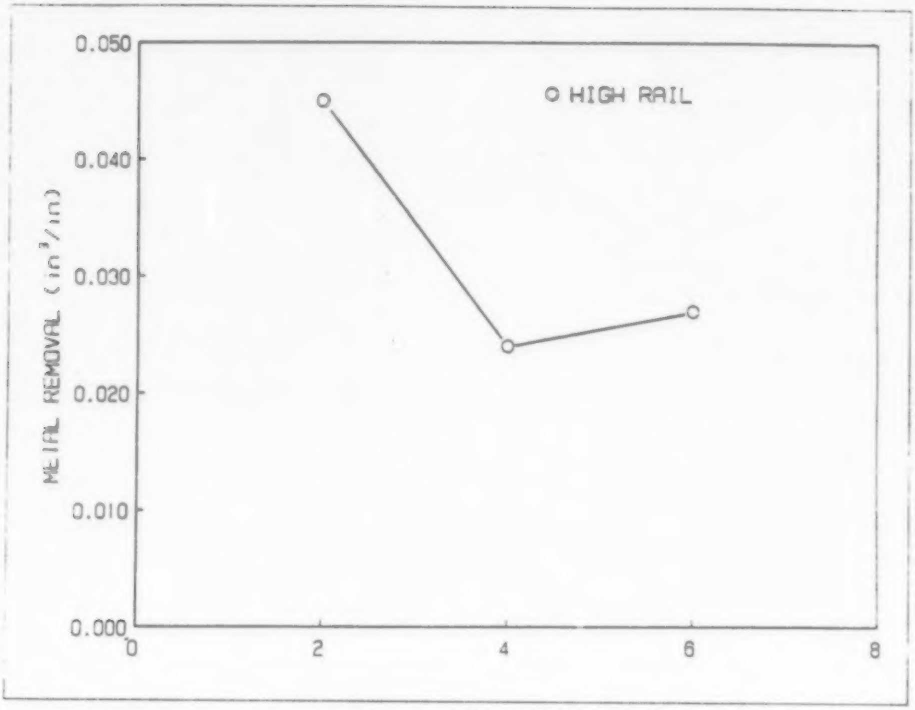

Figure F.3: Metal removal versus speed of grinding on the high rails of the CPR test sites, August 1987 test

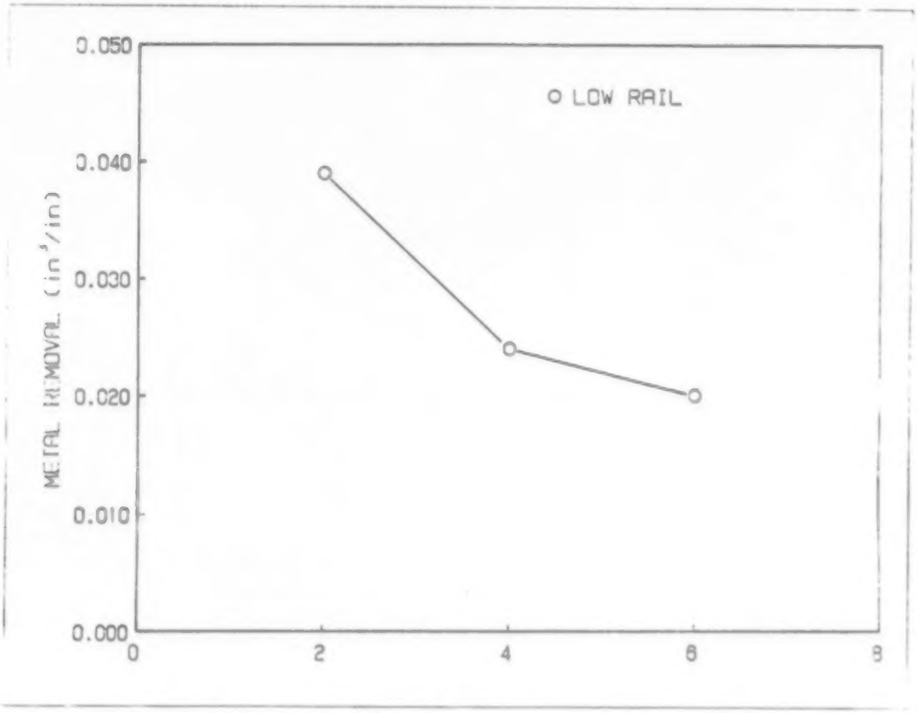

Figure F.4: Metal removal versus speed of grinding on low rails of the CPR test sites, August 1987 test

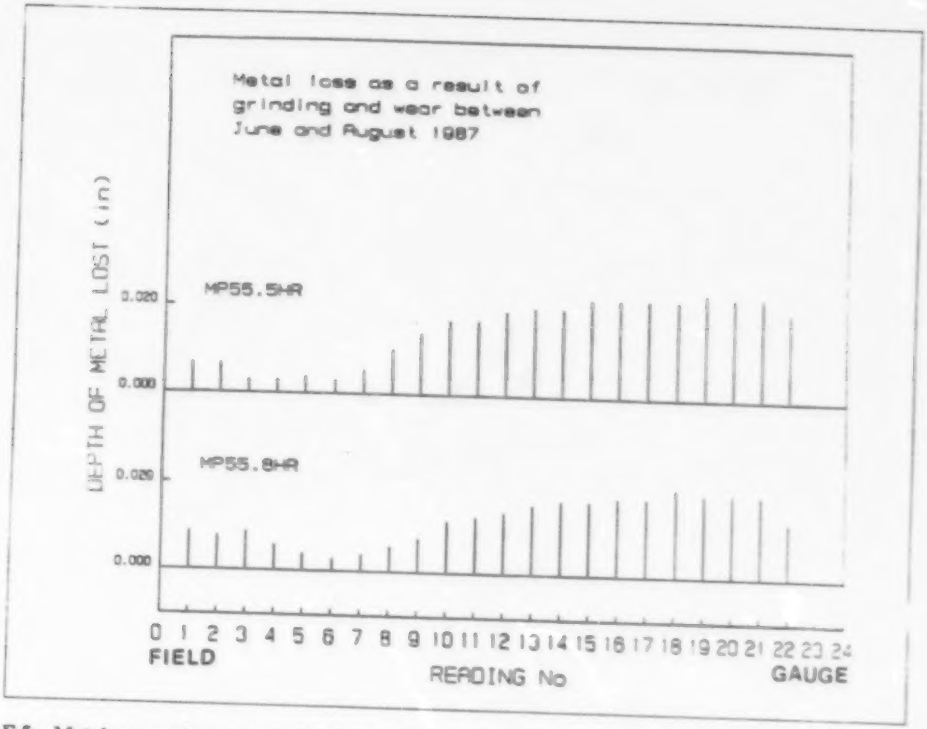

Figure F.5: Metal removal versus speed of grinding on high rails of the CPR test sites during August 1987 test

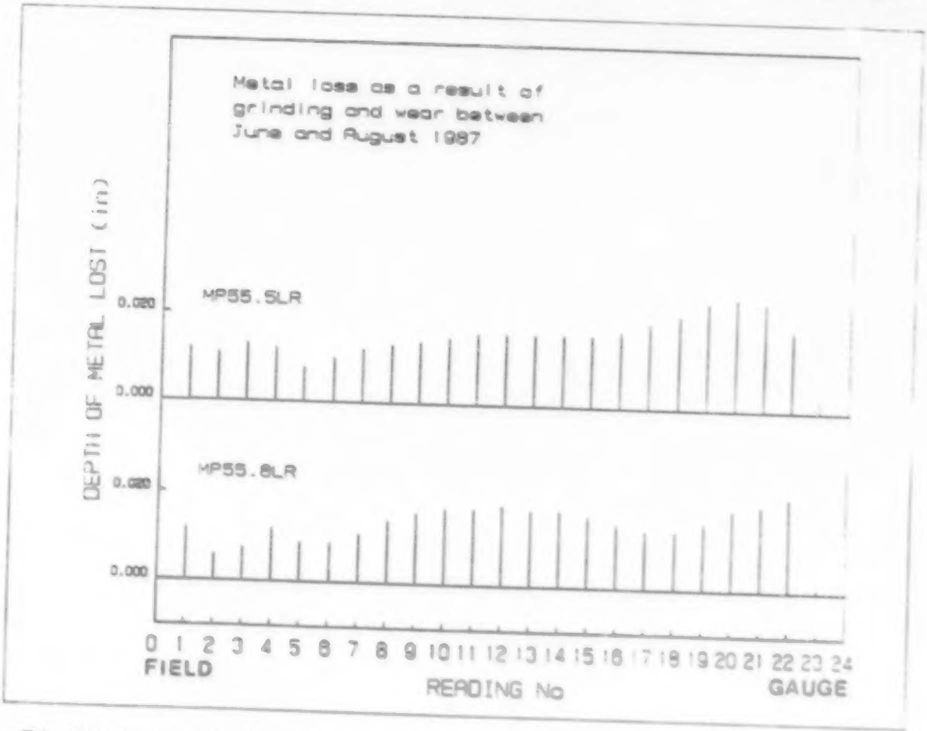

Figure F.6: Metal lost across the low rail heads at CPR test sites due to wear and one grinding cycle over two months

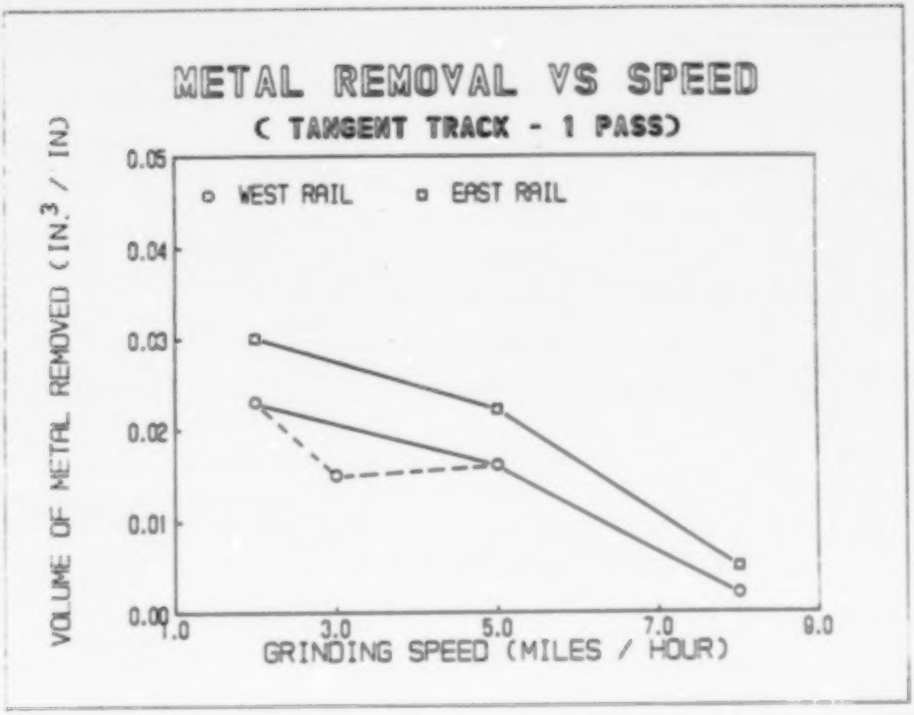

Figure F.7: Graph of volume of metal removed versus grinding speed (tangent track) for BCR September 1986 tests

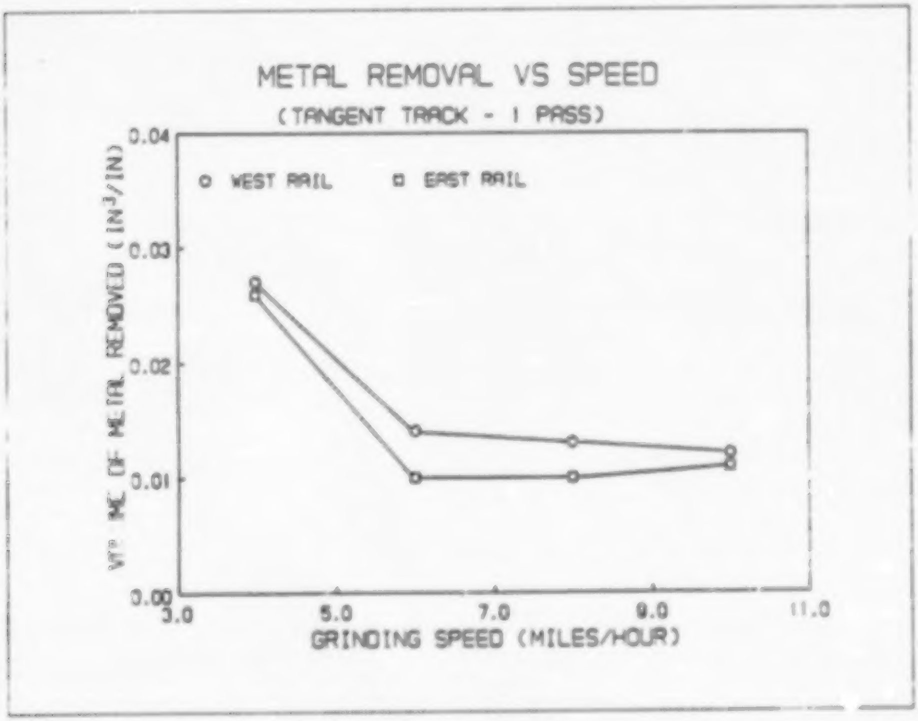

Figure F.8: Graph of volume of metal removed versus grinding speed (tangent track) for BCR September 1987 tests

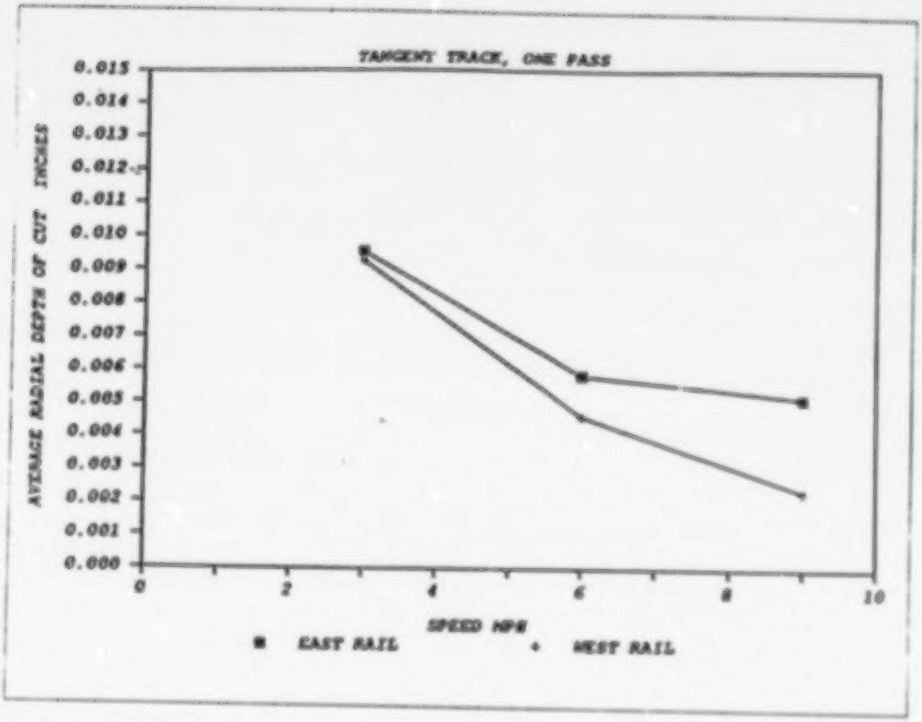

Figure F.9: Depth of cut versus speed on tangent track at BCR test sites, November 1987

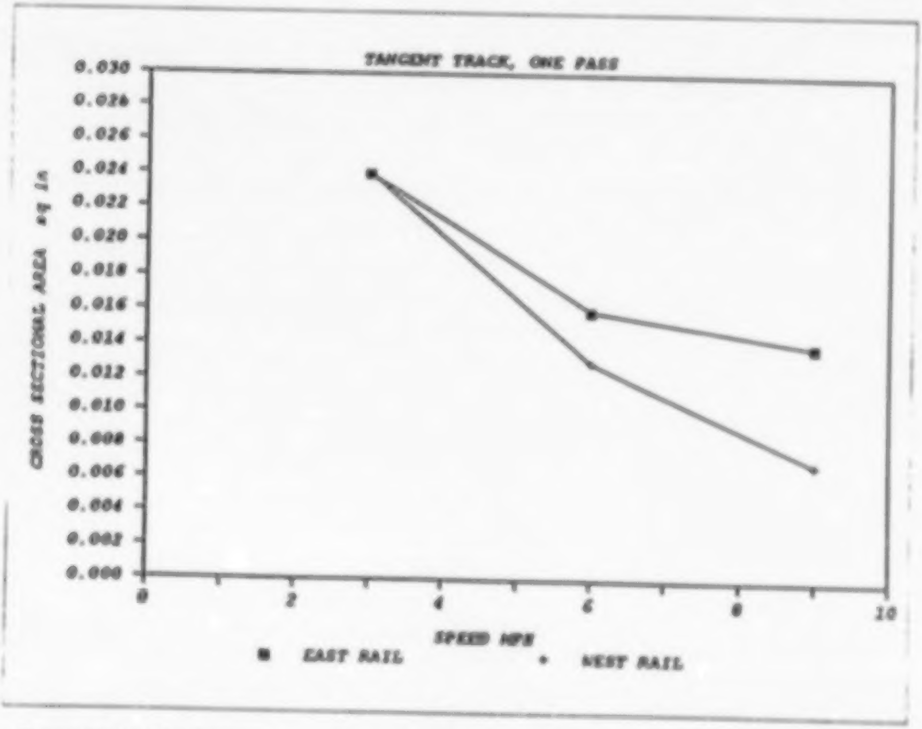

Figure F.10: Metal removal versus speed on tangent track at BCR test sites, November 1987

APPENDIX G

VARIATION OF RAIL INTERNAL STRESS WITH HEAD WEAR — A FINITE ELEMENT APPROACH

G.1 INTRODUCTION G.1
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G.1 INTRODUCTION

One of the prices of heavy-haul operation is the high level of stress to which wheels, rails and other track and vehicle components are exposed. The consequence has been a marked reduction in the fatigue life of these components due to earlier defect initiation and faster growth rate of defects. The industry answered back by increasing wheel and rail sizes to reduce contact stresses as well as reduce the flexural tensile and compressive stresses at the foot and head of rails, respectively. An example is the increased wheel diameter (38 inches (965 mm)) used in unit train operations, aimed at reducing contact stresses at the wheel/rail interface.

To ensure that defects in the form of cracks or short-pitch corrugations, once initiated, do not propagate too deeply into the rail, many railroads are adopting "preventive grinding" policies to replace the conventional "grind-when-you-need-it" policy, better known as "corrective grinding." The ultimate objective of the new trend to prolong rail life is almost a paradox because increased grinding will reduce the amount of material available in the rail section carrying the same load. This implies an increase in the stress level which, although it may not have a significant effect on the interval before micro-crack initiation, will increase the growth rate of transverse defects once initiated, as well as increase the metal removed during the next grinding exercise. Given that the fatigue life of the rail can be increased significantly by the removal of surface defects, what is the limit of head loss that any rail section can accommodate safely, considering that axial tensile stresses up to 30 per cent of the rail yield strength can exist in the rail as a result of extreme temperatures and before the application of external wheel loads?

G.2 OBJECTIVES

The objectives of the finite element analysis reported here were to:

- evaluate the change in rail stresses at the present wear limits in the head of the rail as adopted by Canadian railways;
- compare the stresses mentioned above to those that would exist in a full rail section.

G.3 ANALYTICAL CONSIDERATIONS

To achieve the above objectives, a 3-D finite element analysis of a 136 lb RE (62 kg) rail was undertaken. Due to hardware limitations, the analysis was performed in two stages.

Stage I

Using the beam on elastic foundation (BEF) theory,[1] the location of the zero bending moment along the rail (**Figure G.1**) was obtained by considering it to be of infinite length and resting on an elastic medium. The equation of the rail deformed line shown in Figure G.1 is given as:

---

[1] Hetenyi, M. *Beam on Elastic Foundation.* Ann Arbor, Michigan, 1961.

$$y_x = \frac{P\lambda}{2K} e^{-\lambda x} \left[\cos \lambda x + \sin \lambda x \right] \qquad [1]$$

where: $\lambda = \sqrt[4]{\frac{K}{4EI}}$ and is defined as the characteristic length of the rail

P = wheel load on the rail

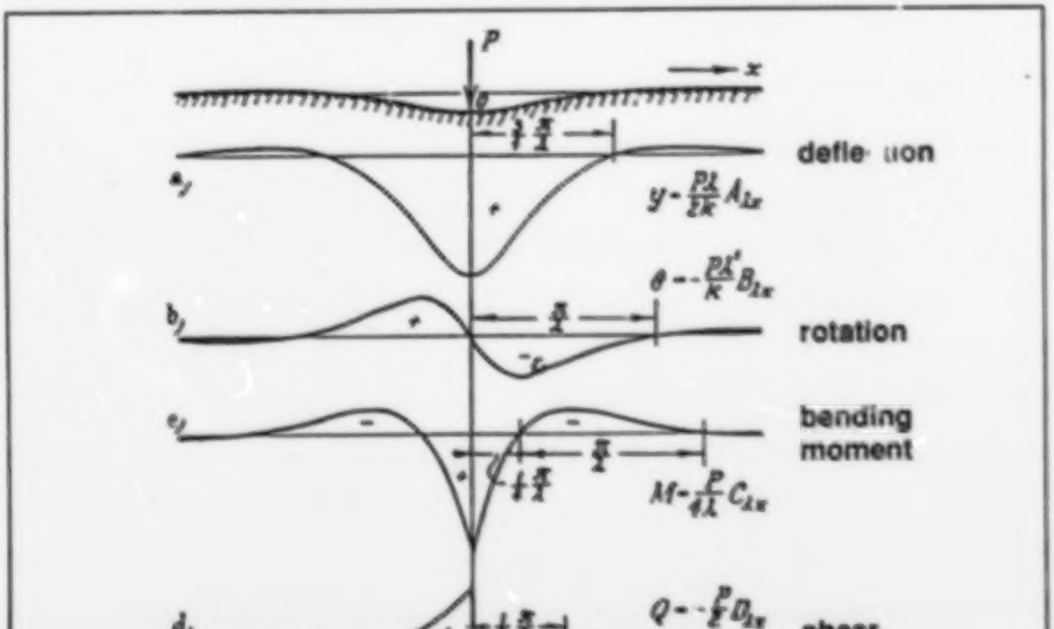
K = foundation modulus

E = modulus of elasticity of the rail

I = rail flexural rigidity about the horizontal axis

$y_{(x)}$ = vertical deformation of positions along the rail

x = distance along rail from point where wheel load is applied.



P
x
a)
deflection
$y = \frac{P\lambda}{2K} A_{\lambda x}$
b)
rotation
$\theta = -\frac{P\lambda^2}{K} B_{\lambda x}$
c)
bending moment
$M = \frac{P}{4\lambda} C_{\lambda x}$
d)
shear force
$Q = -\frac{P}{2} D_{\lambda x}$
+
−

Source: M. Hetenyi, 1961

Figure H.1: Response to beam on elastic foundation to point load P

By double differentiation of equation [1] and rearranging the constants:

$$EIy''(x) = M_x = \frac{P}{4\lambda}e^{-\lambda x}\left(\cos \lambda x - \sin\lambda x \right) \qquad [2]$$

Equating equation [2] to zero, we have

$$\cos \lambda x - \sin \lambda x = 0$$

$$\Rightarrow \tan \lambda x = 1$$

$$or\ \lambda x = \frac{\pi}{4}$$

$$\therefore \quad x = \frac{\pi}{4\lambda}$$

For the full section of 136 lb rail:

$$E = 29{,}000\ ksi,\ I = 94.9\ in^4$$

and for K = 2,500 lb/in/in:

$$\lambda = \left(2.5/(29{,}000 \times 94.9) \right)^{0.25}$$

$$= 0.0309$$

Therefore, the length of rail from the point of wheel load application to the point of zero bending moment is:

$$x_{m=0} = \frac{\pi}{4\lambda} = \frac{\pi}{4 \times 0.309}$$

$$= 25.42\ inches$$

For purposes of comparison, the λ values were calculated for the different rail types available in North America. These are provided in Table G.1. Also, the distance from the point of application of the load to the location of zero bending moment for the each rail is provided.

Table G.1: Characteristic lengths λ for different rails[2]

Rail Type R.E.	A, in^2	I, in^4	λ	x at $M_x = 0$ in
140	13.80	96.8	0.0307	25.58
136	**13.35**	**94.9**	**0.0309**	**25.42**
132	12.95	88.2	0.0314	25.01
119	11.65	71.4	0.0331	23.73
115	11.25	65.6	0.0339	23.17
110	9.95	49.0	0.0364	21.58
90	8.82	38.7	0.0386	20.35

The next step in the calculation was to calculate the reactions at the tie locations for the rail. A tie spacing of 20.5 in (521 mm) was used for a wheel load of 33 kips. Therefore, equation [1] becomes:

$$\frac{P\lambda}{2K} = \frac{33 \times 0.0309}{2 \times 2.5} = 0.2039$$

$$y(x) = 0.2039e^{-0.0309x}\left[\, \cos 0.0309x + \sin 0.0309x \,\right]$$

At x = 0, $\lambda x = 0$:

$$y(o) = 0.2039 \textit{ inches}$$

At x = 20.5, $\lambda x = 0.6335$:

$$y(20.5) = 0.1513$$

---

[2] Please note that these values are only for the foundation modulus of 2,500 lb/in/in.

The tie reaction on the rail at these locations is:

$$R(x) = K \times T.S. \times y(x)$$

where T.S. is the tie spacing = 20.5 inches

$$R_0 = 2.5 \times 20.5 \times 0.2039$$

$$= 10.45 \ \mathit{kips} \ (\ 31.7\% \ \mathit{of\ the\ wheel\ load}\ )$$

$$R_{20.5} = 2.5 \times 20.5 \times 0.1513$$

$$= 7.75 \ \mathit{kips} \ (\ 23.5\% \ \mathit{of\ the\ wheel\ load}\ )$$

Stage II (Finite Element Analysis)

The rail was discretized into 163 nodes on its cross-section (**Figure G.2**) and eight planes along its longitudinal axis (**Figure G.3**). The planes are connected with 6- and 8-node 3-D solid triangular and hexahedral elements (**Figure G.4**). Seven solid elements were used along the 25.42 inches, being the length of rail from point of loading to the section where the bending moment is zero. Since the problem is symmetrical about the transverse plane of the rail, only one-half of the rail was used in the analysis. Due to the asymmetric nature of the loading, symmetry about the vertical plane could not be utilized.

The support reactions of the rail ties at x = 0 and x = 20.5 inches were distributed across the bottom of the rail according to the tributary area of the bottom elements. A hinge-type support was placed at the location where the bending moment is equal to zero. This allows the end to transmit shear but not bending moment.

G.4 BOUNDARY CONDITIONS

Boundary conditions reflecting real life situations were imposed at all the nodes so as to simulate deformation characteristics. Figure G.3 shows the elevation of the rail and the support conditions. All intermediate nodes were allowed to translate in any of the three global axis as well as to rotate about these axes. At section B-B, the nodes were only allowed to rotate about the x axis. All other degrees of freedom were fixed. In section A-A only translation about the y axis and rotation about the z axis were allowed.

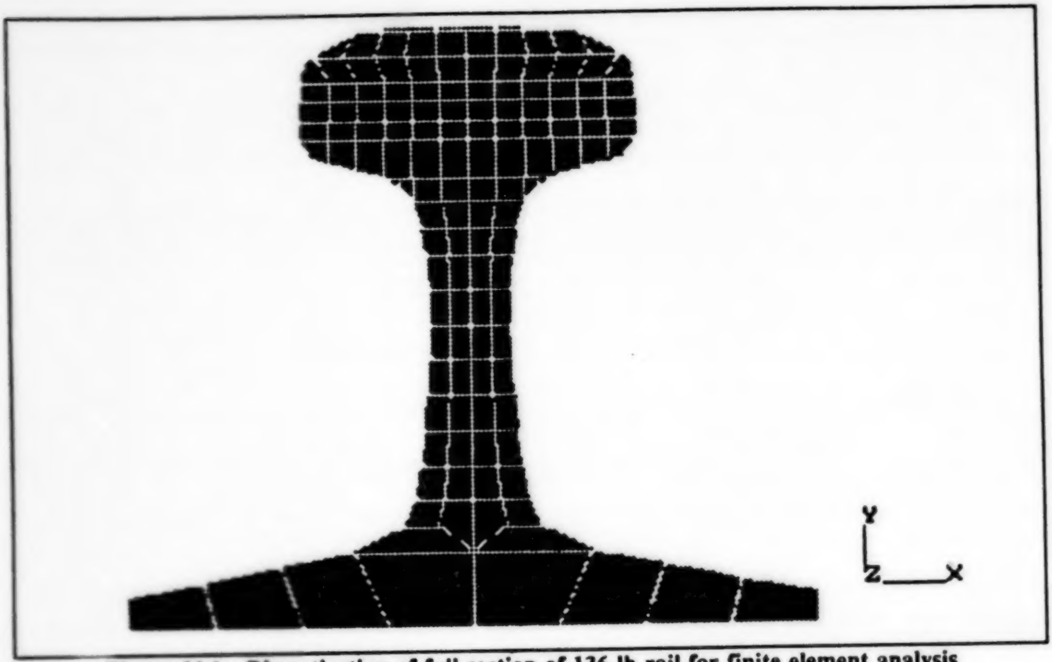


Figure 2(a): Discretization of full section of 136 lb rail for finite element analysis

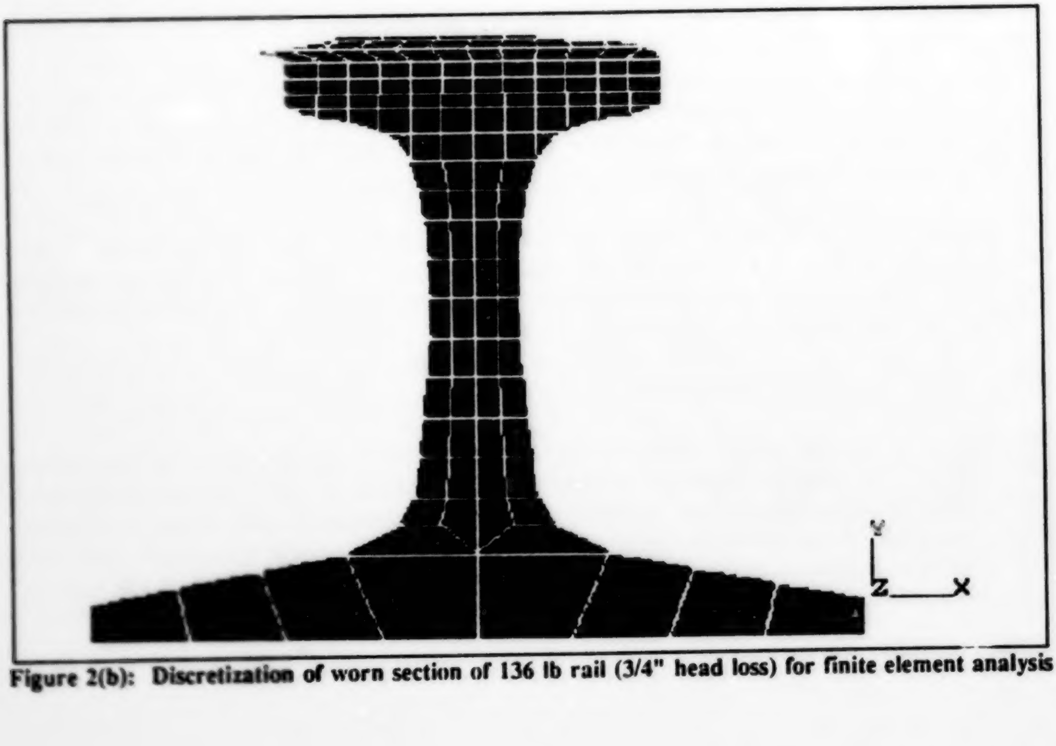
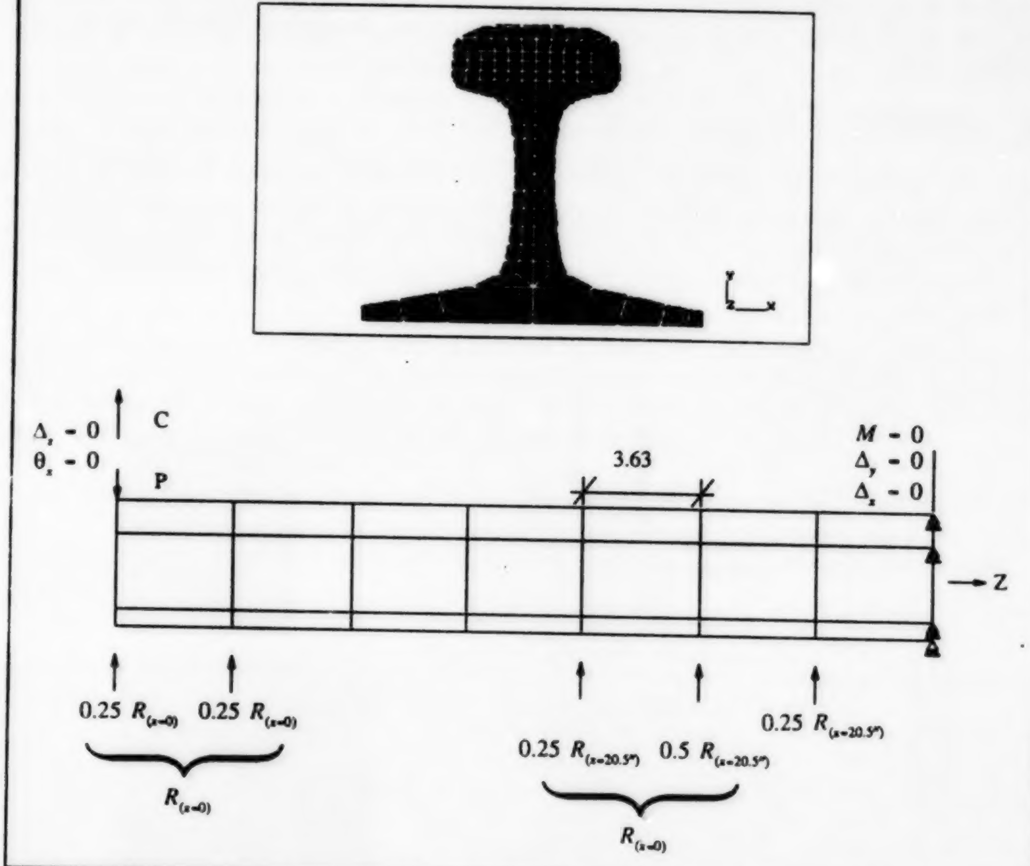
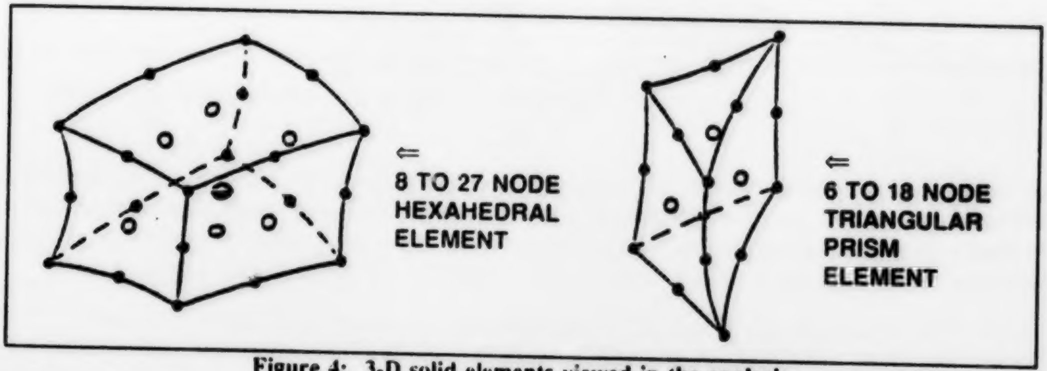


Figure 2(b): Discretization of worn section of 136 lb rail (3/4" head loss) for finite element analysis



$\Delta_z = 0$
$\theta_x = 0$
C
P
3.63
$M = 0$
$\Delta_y = 0$
$\Delta_z = 0$
Z
$0.25\ R_{(z=0)}$
$0.25\ R_{(z=0)}$
$R_{(z=0)}$
$0.25\ R_{(z=20.5")}$
$0.5\ R_{(z=20.5")}$
$0.25\ R_{(z=20.5")}$
$R_{(z=0)}$
y
z
x

Figure 3: Elevation of rail section used in the finitie element analysis showing boundary conditions



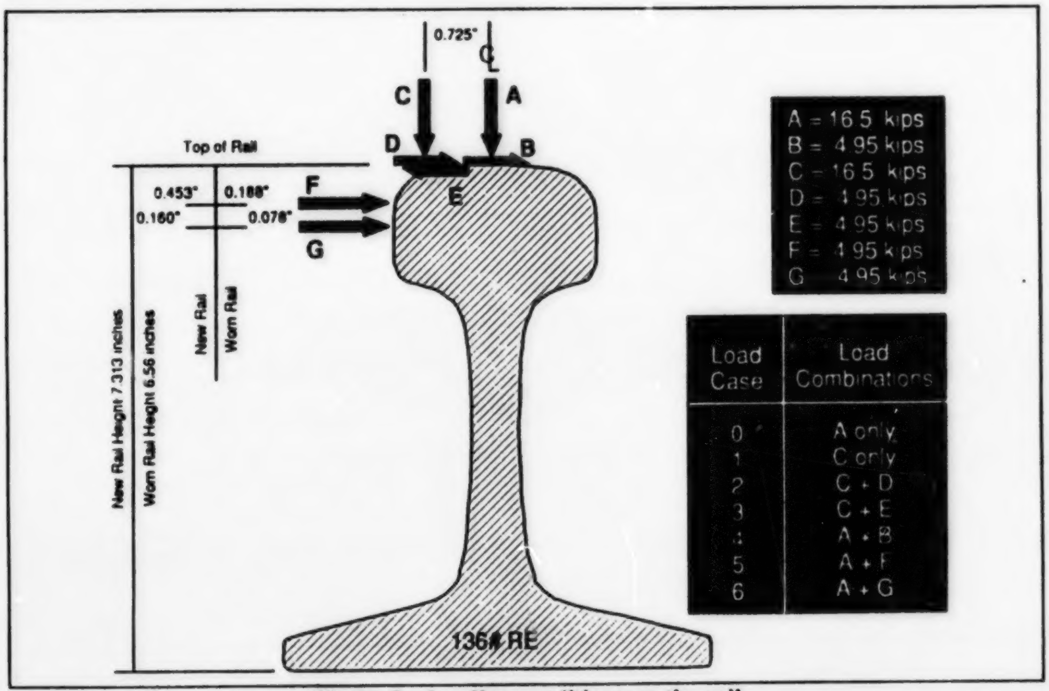
8 TO 27 NODE HEXAHEDRAL ELEMENT
6 TO 18 NODE TRIANGULAR PRISM ELEMENT

Figure 4: 3-D solid elements viewed in the analysis

The analysis was performed using the finite element program *SCADA*.[3] The limitations on the number of nodes and elements used in the analysis were restricted by the hardware. Analysis was performed on a full and a worn section of 136 lb rail. The worn section was based on a vertical head wear of 3/4 inches. Due to time and funding restrictions, the analysis was limited to rails on tangent track.

G.5 LOADING

Loads were applied to the rail top to simulate the various loading conditions to which the rail could be exposed. Horizontal frictional forces were also applied to the rail simultaneously with vertical forces to simulate vehicle hunting. Force due to wheel flange contact with the rail head was also considered. Combinations of these forces are depicted by the seven load cases illustrated in **Figure G.5**.



A = 16.5 kips
B = 4.95 kips
C = 16.5 kips
D = 4.95 kips
E = 4.95 kips
F = 4.95 kips
G = 4.95 kips

Load Case	Load Combinations
0	A only
1	C only
2	C + D
3	C + E
4	A + B
5	A + F
6	A + G

Figure 5: Loading conditions on the rail

An arbitrary vertical wheel load of 16.5 kips was used in the analysis. Assuming a 30 per cent coefficient of friction between wheel and rail, a maximum frictional force of 4.95 kips was obtained. This was also used as the flange contact force, although it could be larger in real life situations. Since this was an elastic analysis, the results can be scaled to any axle load.

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[3] *SCADA, Version 4.03*. American Computers and Engineers, Los Angeles, California 90049, USA.

G.6 RESULTS OF THE ANALYSIS

To represent the stresses in the rail, and to accommodate the three-dimensional nature of these stresses, the von Mises stresses[4] were calculated. von Mises stresses are calculated on the basis that the portion of the strain energy causing volume change in the material will not be effective in causing failure by yielding. Hence, only strain energy causing distortion is considered. This theory has been found to agree best with test data for ductile materials.[5] The stress values are directly comparable to results from tensile strength tests.

Outside the wheel/rail contact zone, the state of stress in the rail head was found to increase by up to 100 per cent for both the full and worn sections from load case 0 (Figure G.6) to load case 3. Load case 3 also produced the worst effect in the rail web for both full and worn rail analysis. A summary of the maximum rail head stresses (outside the contact zone) is given in Table G.2. Photos of the stress contours produced by load case 3 in the full and worn rails are shown in **Figures G.6** and **G.7**. An examination of the stresses supports the original contention that grinding will increase the overall state of stress in the rail head and the web area. The effect of metal removal from the rail head on the rail base is minimal.

Figures G.8 and **G.9** show the changes in the state of stresses in the rail between load cases 2 and 4 for the full rail section. Of particular interest are the head and web stresses which show significantly differing patterns, although the value of the stress at about the neutral axis remains approximately constant.

Table G.2: Resulting Finite Element Model Analysis

Load Case	Maximum Rail Head Stresses*	
	Full	Worn
0	10.16	13.11
1	13.64	21.10
2	16.66	21.09
3	22.25	37.48
4	18.25	24.51
5	18.08	21.80
6	16.04	22.88

* All stresses are in ksi and are outside the wheel/rail contact zone.

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[4] Frequently called the Huber-Hencky-von Mises theory, because it was proposed by M.T. Huber of Poland in 1904 and independently by R. von Mises of Germany in 1913. The theory was further developed by H. Hencky and von Mises in Germany and the United States.

[5] William F. Riley and Loren Zachery. *Introduction to Mechanics of Materials*.
A.C. Ugural and S.K. Fenster. "Advanced Strength and Applied Elasticity." Elsevier.

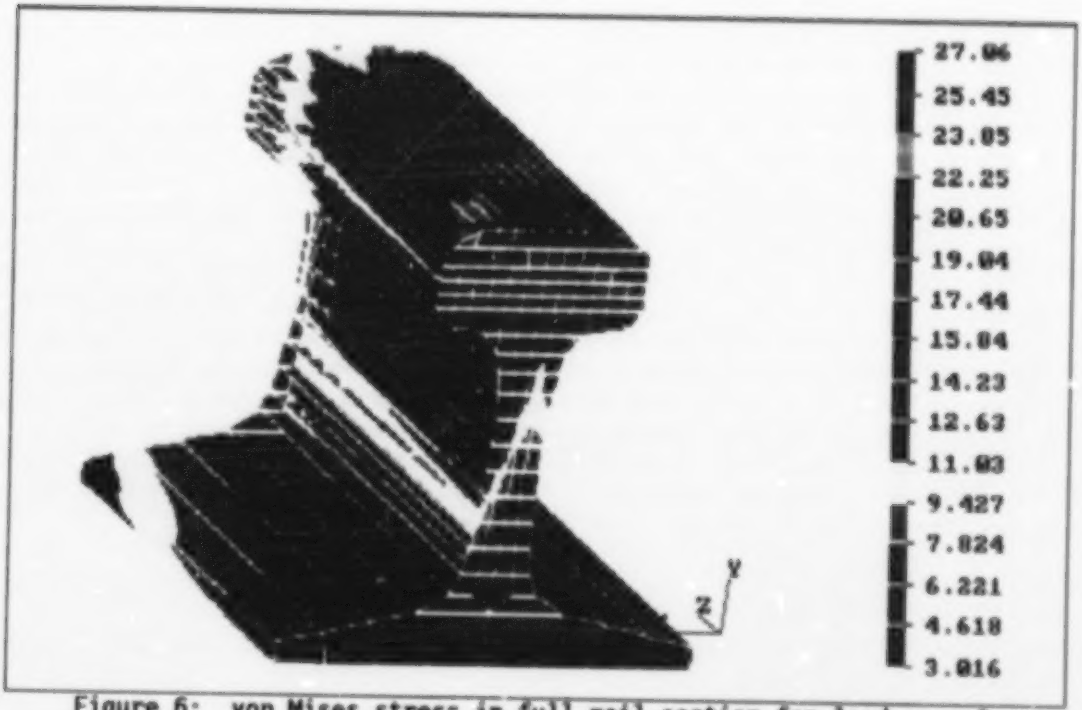
27.06
25.45
23.85
22.25
20.65
19.04
17.44
15.84
14.23
12.63
11.03
9.427
7.824
6.221
4.618
3.016
y
z

Figure 6: von Mises stress in full rail section for load case 3

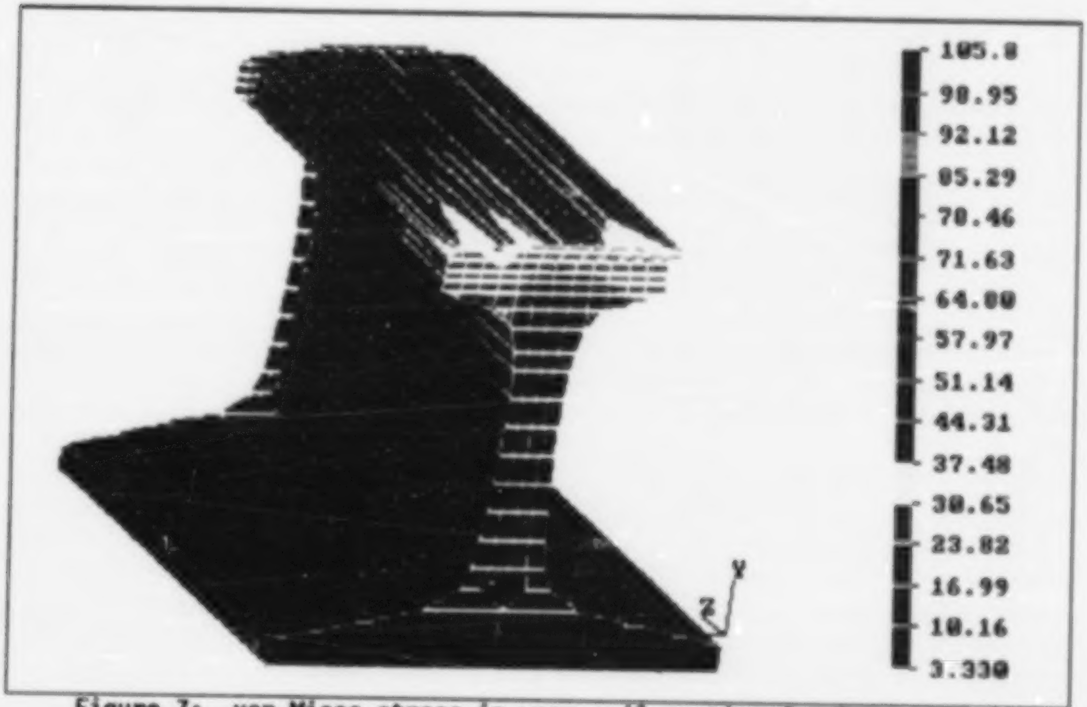
105.8
98.95
92.12
85.29
78.46
71.63
64.80
57.97
51.14
44.31
37.48
30.65
23.82
16.99
10.16
3.330
y
z

Figure 7: von Mises stress in worn rail section for load case 3

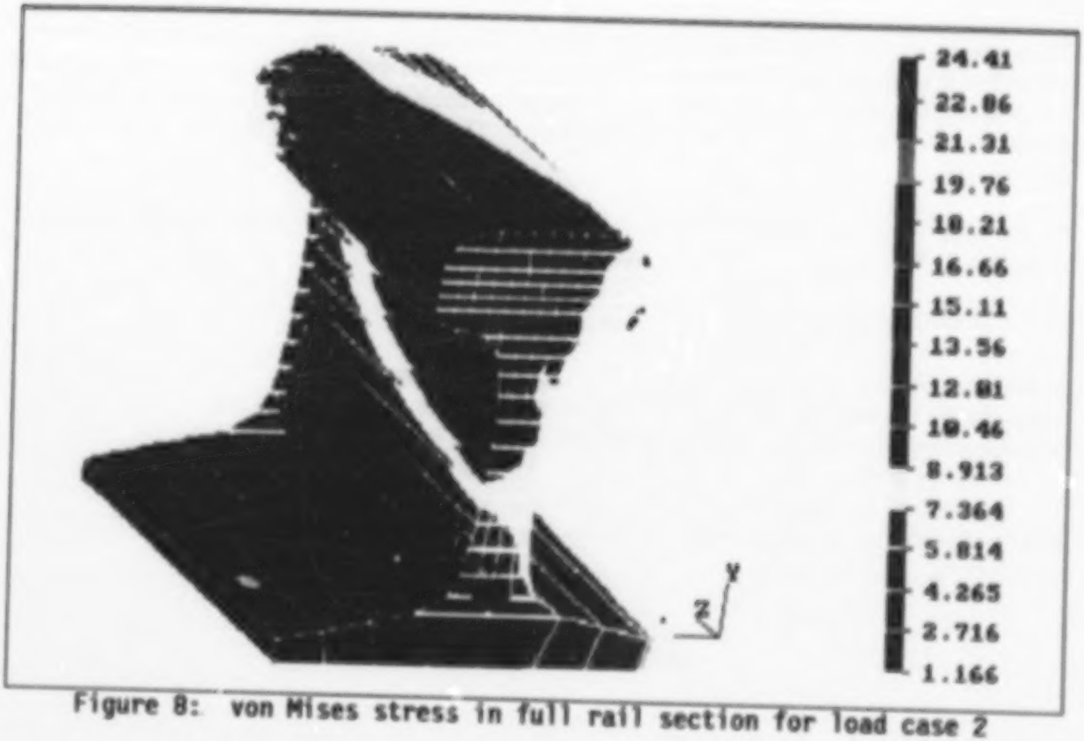
24.41
22.86
21.31
19.76
18.21
16.66
15.11
13.56
12.01
10.46
8.913
7.364
5.814
4.265
2.716
1.166
Y
Z

Figure 8: von Mises stress in full rail section for load case 2

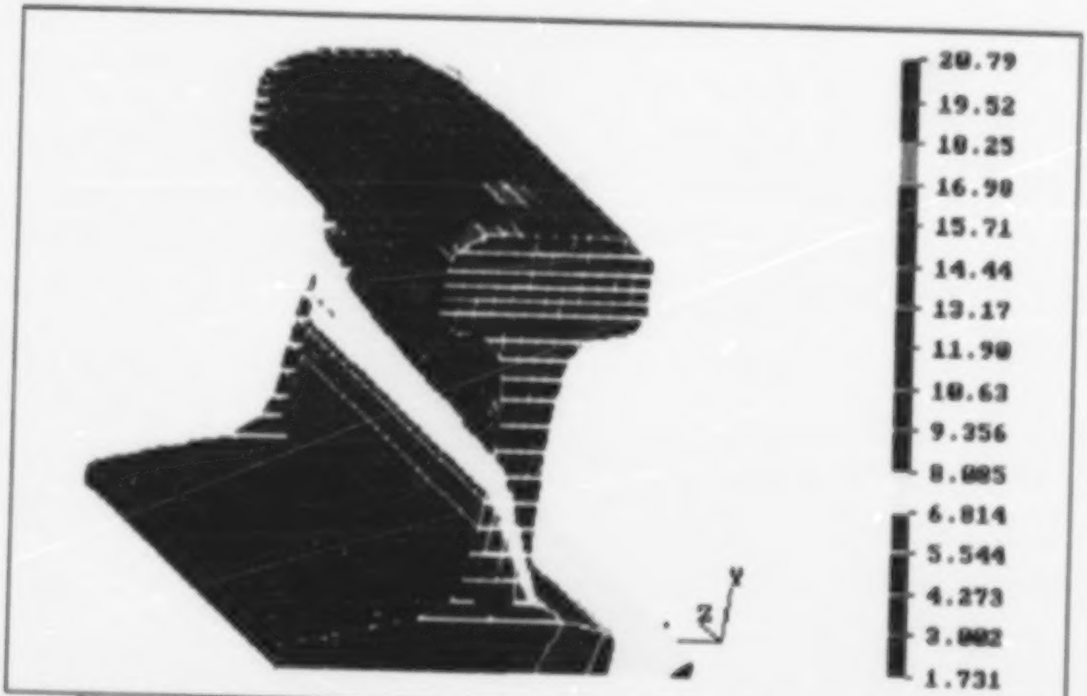
20.79
19.52
18.25
16.98
15.71
14.44
13.17
11.90
10.63
9.356
8.085
6.814
5.544
4.273
3.002
1.731
Y
Z

Figure 9: von Mises stress in full rail section for load case 4

These results clearly show that the increase in the rail stresses in the web and head areas will not jeopardize the rail by causing premature failure. Instead, there would be a slight decrease in the rail fatigue life. Also, in the presence of a defect in the rail head, the crack tip stress intensity at the defect will increase with the wear of the railhead. This would cause an increase in the defect growth rate.

On the other hand, the pattern of residual stresses in the head and web areas and their changes through time would also influence the defect growth rate.

G.7 CONCLUSION

It has been shown, using finite element analysis, that the general state of stress is altered and increased by the removal of metal from the railhead due to wear and grinding. Under normal circumstances, the resultant increase in stresses in a rail is such that it should not be of grave concern to the track engineer. In the presence of internal rail head defects, the defect growth rate will be increased by grinding but the rate increase is not known at present. It is also evident that increased wear limit on the railhead is possible, provided that the rail does not fail in fatigue prior to achieving that new limit.

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